Range Commanders Council

DOCUMENT 382-94

METEOROLOGY GROUP

A GUIDE
FOR QUALITY CONTROL
OF SURFACE METEOROLOGICAL DATA

WHITE SANDS MISSILE RANGE
KWAJALEIN MISSILE RANGE
YUMA PROVING GROUND
DUGWAY PROVING GROUND
ELECTRONIC PROVING GROUND
COMBAT SYSTEMS TEST ACTIVITY

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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
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SPACE AND MISSILE SYSTEMS CENTER,
SPACE TEST AND EXPERIMENTATION PROGRAM OFFICE

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A GUIDE
FOR QUALITY CONTROL
OF SURFACE METEOROLOGICAL DATA

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Prepared by

METEOROLOGY GROUP
RANGE COMMANDERS COUNCIL

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PREFACE

This document was prepared by the Range Commanders Council (RCC) Meteorology Group (MG) to satisfy the requirements of task MG-18, Develop a Guide for Quality Control of Surface Meteorological Data. This task was undertaken by the Standing Committee on Meteorological Measurements with Mr. Christopher Biltoft as chairman. Document review and comment were provided by the following MG members:

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INTRODUCTION

Quality control (QC) should be an integral part of any data collection program. The impetus to perform quality control is derived from management's quality assurance (QA) program. The QA program is the collection of planned and systematic actions defined by management as those necessary to provide confidence that a product or service will satisfy customer quality requirements. This program should be defined in management's quality policy and implemented through a quality system that includes the organizational structure, responsibilities, procedures, processes, and resources for implementing quality management. Quality control includes the operational techniques and activities needed to fulfill QA program requirements (ANSI/ASQC, 1987). Further impetus towards quality assurance comes from increased scrutiny of and accountability for environmental impacts of range activities and the need to meet International Standards Organization (ISO) standards. This guide is intended to assist ranges in the development and maintenance of an acceptable quality control program for surface meteorological data.

CHAPTER 1

QUALITY CONTROL GENERAL PRINCIPLES

1.1 Product and Quality Control

The range meteorologist's job is to provide valid and relevant information to the customer. To achieve this goal, the information must be supportable by documentation. Validity can be defined using instrument performance and calibration records and a description of the steps used to process the data. Relevance, which includes the timely dissemination of representative and pertinent information in a user-friendly format, is as important as validity to a successful measurement program. Collecting valid but irrelevant data contributes nothing to program objectives and wastes resources. To provide the customer with a quality product, a measurement program's quality control (QC) plan should include procedures designed to meet the program's requirements in terms of validity and relevance and to present this valid, relevant information in an accessible and useful format. Consequently, QC must begin with a clear definition of program objectives that can be satisfied by a specific product set. Product definition is followed by careful identification of relevant measurement requirements, instrumentation, and sites.

An optimum QC program includes proactive identification and avoidance of potential errors as well as error checking procedures. The QC process starts before a measurement program and might proceed as described in the following subparagraphs.

1.1.1 Requirements Definition. Detailed information regarding the measurements (and allowable measurement uncertainties) needed to provide that information, and the instrumentation used to obtain those measurements.

1.1.2 Calibration/Certification. A measurement comparison made against an accepted standard or transfer standard or against some standard in a functional test, as appropriate.

1.1.3 Instrument and Site Selection. Choosing instruments and measurement sites that provide representative measurements of pertinent variables.

1.1.4 Meteorological Limitations. Go/no-go controls or restrictions imposed upon the mission or measurement program.

1.1.5 Deployment. Installation of the instruments and completion of field checks and reasonableness (consistency) checks.

1.1.6 Flagging. Identification of out-of-range or out-of-tolerance conditions.

1.1.7 Monitoring. Real-time review of incoming data as needed to satisfy mission requirements.

1.1.8 Analysis. Review of summary statistics and plots derived from the data set. Performing flagging/de-flagging, spike removal, and trend analysis.

1.1.9 Report Preparation. Conversion of the data into meaningful information that is supported by documentation of the instrumentation, measurement, and analysis processes.

1.1.10 Modeling. Applying the information through prototypes to generate new knowledge or understanding of meteorological processes.

The goal of QC is to provide the desired product to both the external customer who funds the program and to the internal customer who is the performing organization itself.

1.2 Experimental and Mission Support Processes

The activity of generating meteorological information generally follows one of two general processes: (1) the Experimental Process, or (2) the Mission Support Process. Each process consists of a series of actions and products. Quality Control is embedded within each of the actions taken to produce the desired products. Some QC procedures are more appropriate for one process than for the other. Selecting the appropriate QC procedures for a process is vital to the design of a QC program.

The Experimental Process begins with a question that leads to a test or experiment that produces an initial product (data). The data are validated and analyzed to produce information as the next product. The process continues through modeling to produce knowledge, which serves as a basis for hypothesizing new questions or theories that lead to further testing and the generation of new data sets. The continuous aspect of this process has QC inherently embedded within it; errors surface as inconsistencies that trigger review, re-analysis, corrective action, and re-testing. The Experimental Process can be viewed as an ongoing ascending spiral of actions and products. The upper half of figure 1-1 is a two-dimensional representation of the Experimental Process spiral with actions

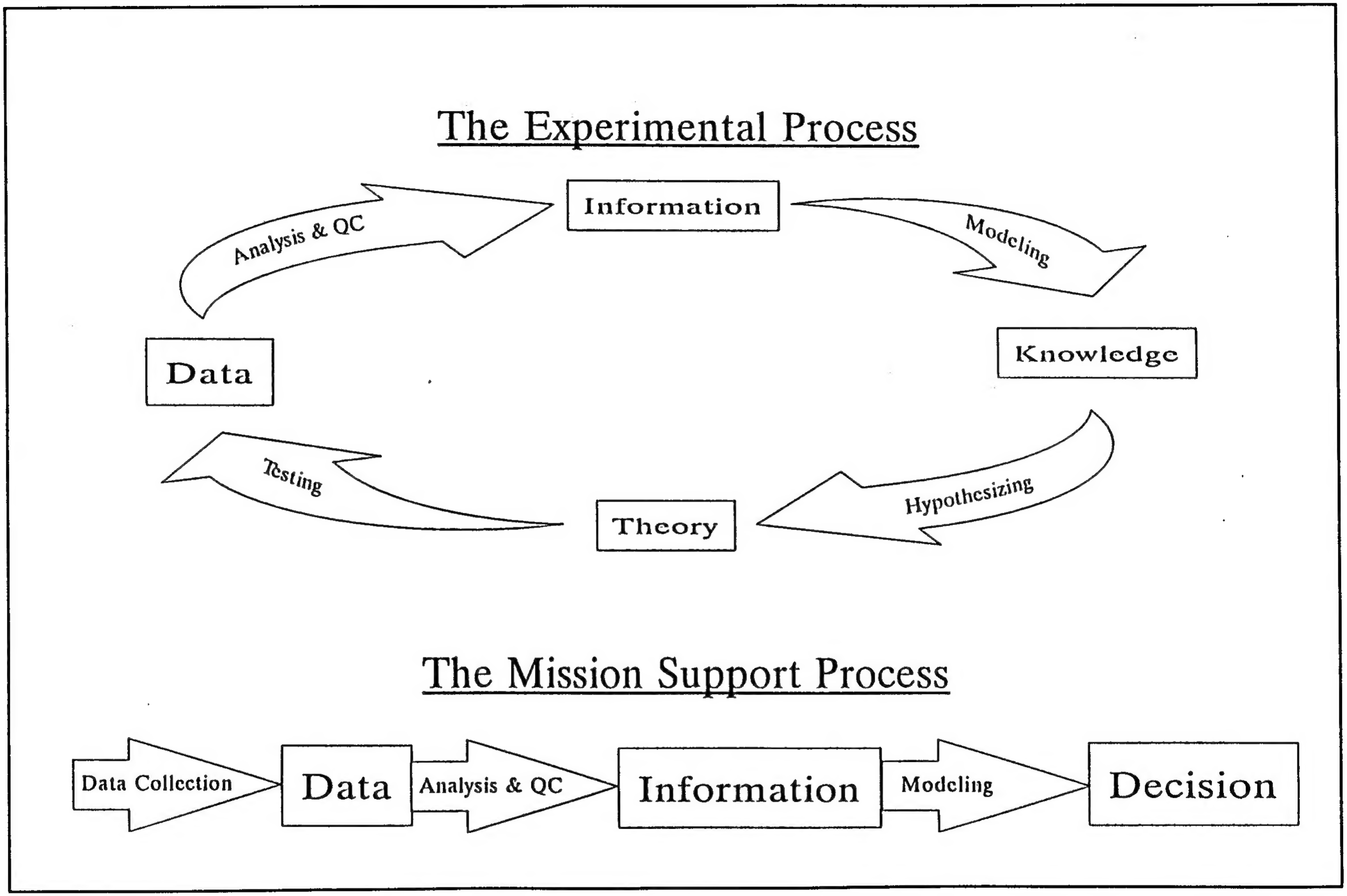

Figure 1-1. The Experimental Process and the Mission Support Process.

illustrated as arrows and products illustrated as boxes. This figure describes the process of scientific inquiry as it might be performed in university and research settings. Data collection, analysis, and archival for climatological purposes may also follow the Experimental Process.

Meteorological data obtained in the Experimental Process are as inclusive as possible within experimental and budgetary limitations. The majority of the QC is performed well after data collection has been completed when there is time for reflective analysis and interpretation. Data are carefully formatted, annotated, and archived for future use. Unexpected results such as anomalous readings or outlier data points are often the subject of intense scrutiny. Quality-control procedures, which may include the use of complex statistical or analytical techniques, are reported in detail for peer review, where the data and their processing procedures are subject to re-analysis and alternate interpretations. The Experimental Process employs the principles of the scientific method to identify and to preclude the retention of error. The discovery of error often leads to new measure-magnet methods or experimental procedures designed to eliminate those errors.

The Mission Support Process more closely resembles the activities at test ranges where real-time go/no-go decisions must be made within a time constraint. Unlike the Experimental Process, the Mission Support Process is driven by user-defined start and end times. These times are often determined by factors beyond the control of the data analyst, who must produce timely information on which critical mission decisions will be based. The lower half of figure 1-1 illustrates the Mission Support Process. Data collected for mission support are analyzed and validated to the point where information is available for decision making and not necessarily to the point where sufficient knowledge accumulates to identify all errors or to take cogent corrective actions. The emphasis is on producing consistent information to support (or refute) existing expectations (forecasts) of meteorological conditions. Outliers must be either accepted as unanticipated results or rejected as erroneous data based on the judgement of the on-duty analyst. Measurement redundancy is often needed to ensure a reasonable degree of success in having the required valid information available before decision dead-lines. Data validation often is based on rule-based "either/or" criteria rather than detailed statistical analyses. Mission-support information is usually presented in brief statistical summaries, while the raw data are stored in unique formats that are difficult to use outside the originating test center. Archival is not performed with a view to re-analysis or for peer review, so the data often do not resurface unless something goes wrong with the mission. The Mission Support Process, unlike the Experimental Process, is not self-checking. A conscious effort is needed to build quality checks into the data collection and analysis phases of the Mission Support Process. This guide is designed to assist the range meteorologist with that requirement.

1.3 Validation

Meteorological measurement-system validation includes some combination of calibration, on-site system checks, and functional testing. Its purpose is to assure the user that the measurement system is performing to a known standard. Calibrations usually verify system-component response over a desired range or span, while system checks verify the integrity of signal transfer through the measurement system. Functional testing includes a statistical method to compare the performance of instruments measuring the same phenomena under field conditions. Results of calibrations, system checks, and functional testing are expressed using terminology presented in table 1-1. Documentation (log records) of calibration, maintenance, and system checks is needed to defend measurement validity.

1.3.1 Validation and Accuracy. System validation usually includes a statement of performance in terms of comparability or accuracy. This statement should address the entire system not just component parts. Total measurement-system accuracy is the product of uncertainties attributable to the sensor, electronic-data transmission, and data-logging process. Sensor response includes an analog or digital signal derived from the sensor's interaction with the environment. This signal is then subject to line losses or noise during transmission to a recording device. The recorder also contributes its noise threshold to total system noise. Measurement accuracy is maximized by choosing a compatible sensor/recorder combination, careful grounding and cabling procedures, filtering, and flagging suspect data for review. Independent errors occurring at each step in the process result in a total error that is equal to the square root of the sum of the squares of each contributing error.

1.3.2 Calibration. Instrument calibration is the first step in defining data validity. Calibration involves comparison against a known standard to determine how closely instrument output matches the standard. Performance of a laboratory calibration carries the implicit assumption that the instrument's characteristics are sufficiently stable to retain that calibration in the field. A calibration history established over successive calibrations can provide confidence in the instrument's stability.

Laboratory calibration may define a bias which can then be removed through mechanical, electrical, or software adjustment. The remaining random error or imprecision is not repeatable and cannot be removed, but it can be statistically defined through a sufficient number of measurement repetitions during calibration. The combined effect of all random (uncorrelated) uncertainties can be obtained from the square root of the sum of the squares of the individual uncertainties.

TABLE 1-1. DEFINITION OF TERMS

Accuracy: The absolute uncertainty in a measurement obtained by comparison against an accepted standard in a carefully controlled environment; the degree to which a measurement corresponds to a "true" value which is never absolutely known. In practical applications, an instrument's accuracy is determined by comparison of its measurements to corresponding measurements made by a "standard" instrument with differences expressed as a "bias" plus or minus a random uncertainty or precision.

Bias: The mean difference between averaged readings of the test instrument and the standard instrument to which it is compared.

Comparability: The root mean square (rms) of the difference between readings of two or more instruments of different design sampling the same variable in an uncontrolled field environment.

Functional Precision: The rms of the difference between readings of two or more instruments of the same design sampling the same variable in the same environment.

Precision: Response of the measuring instrument to changes in the measured variable. Components of precision include resolution and repeatability.

Repeatability: The ability of an instrument to return to a known measurement or position after being cycled through its operating range.

Range: The span of measurement which extends from the threshold to the maximum measurable value.

Resolution: The least significant digit reading which defines the smallest variation in the variable input that causes a detectable change in instrument output. It is given as a fractional part of the measurement scale.

Sampling Interval: The period between successive instrument readings. Considerations are given to sample-size requirements, instrument-time constant, data-logging speed and capacity, and measurement influence sampling interval purpose.

Threshold: The smallest measurable input.

Time Constant: A measure of an instrument's rate of response to a step change in the measured variable. It is the time required for the instrument response to reach $|1-1/e|$, or 63 percent, of the new equilibrium value.

Calibration should define an instrument's bias or average deviation from its reference standard, the range over which the calibration is valid, and the existence of any thresholds or nonlinear response regions. It should also define an instrument's resolution, which is the smallest change in input that produces a measurable change in output. Hysteresis, which represents the instrument's imperfect ability to gain or shed energy, should be identified by cycling the sensor over its operating range during calibration.

The pedigree of a calibration depends on its traceability (MIL-STD-45662A, 1980). Traceability is defined by a hierarchy of standards. The primary standard is the ultimate reference with respect to fundamental physical quantities (mass, length, time) and offers the highest obtainable precision. Primary standards reside within major national or international institutions. Primary standard instruments are usually impractical for field measurements. Secondary standards are traceable to a primary standard. These instruments often reside in major calibration laboratories and are usually impractical for field use. Working standards are usually laboratory instruments that have been calibrated against a secondary standard. Working-standard instruments that are actually taken to nonlaboratory sites are known as transfer standards. Transfer standard instruments can be used to compare instruments in a laboratory (Lockhart, 1987) or the field (Lockhart, 1989B).

Traceability to a recognized standard is available for some meteorological instruments. The National Institute for Science and Technology (NIST) (formerly National Bureau of Standards) maintains a piston-gage standard for pressure, an International Practical Temperature Scale (IPTS-90) for temperature, low- and high-speed wind tunnels for wind speed, and a gravimetric device for humidity (Brock and Nicolaidis, 1984). The World Meteorological Organization (WMO) maintains an absolute cavity pyrheliometer at Davos, Switzerland, with a secondary National Oceanic and Atmospheric Administration (NOAA) standard in Boulder, Colorado. When no recognized standard is available, a consensus standard may be established to provide a measure of relative agreement between instruments (MIL-STD-45662A).

When possible, it is desirable to have a calibration referenced by secondary or transfer standards to NIST and measurement procedures referenced to a standards organization such as the American Society for Testing and Materials (ASTM) that is approved by the American National Standards Institute (ANSI). These standards are available for some types of instrumentation, but for others, especially those representing newer technologies, they are largely unavailable. Standards are most often available for instruments that produce analog voltage or current outputs that can be checked statically from mounting jigs or isothermal baths or dynamically in a wind tunnel. In general, industry standards have not kept up with advances in remote sensing and microprocessor technology.

Microprocessors typically perform some degree of processing or interpretation of a sensor's output, which complicates calibration. In the absence of industry standards, an instrument's manufacturer should provide calibration and performance guidance. Initial calibration cycles may require adjustment because of the instrument's exposure to harsh, corrosive environments or severe weather events.

A logbook or record of an instrument's calibration history, supported by whatever calibration documentation is available, should be kept on file for reference and should accompany each instrument returned to a laboratory for calibration. Each calibration log should include the instrument's departure from its standard as it enters the laboratory for calibration. The calibration deviation can then be compared with the instrument's measurement accuracy requirements. Calibration intervals should initially follow manufacturer's recommendations. An instrument that establishes a record of deviations that fall within acceptable accuracy limits may be returned for calibration at less frequent intervals. Conversely, an instrument that consistently arrives at a calibration facility in an out-of-tolerance condition may require replacement or more frequent calibrations.

The NIST traceability cannot be the sole basis for evaluating the validity of an instrument's reading. Instrumentation for which traceability to a NIST primary or secondary standard has not been established can produce valid data if referenced to a fundamental principle. For example, no NIST standard exists for a sonic anemometer/thermometer, but speed-of-sound propagation is fundamentally related to the temperature of the propagation medium. The propagation of an acoustic wavefront in a still (zero wind) chamber containing a pure gas at a known temperature provides a fundamental basis for calibration. A zero-wind check in air provides a method to verify calibration stability in the field. Conversely, a manufacturer's claim that a sensor is "NBS or NIST traceable" may be of little value if it leads to an accepted standard through a long, undocumented calibration trail with compounded uncertainties. The NIST cannot guarantee the accuracy or precision of a commercial instrument even if it is described as "NIST traceable." Traceability can be established through an accredited calibration laboratory such as the Test Measurement and Diagnostic Equipment (TMDE) Facility at Redstone Arsenal.

1.3.3 Functional Testing. Calibration provides a necessary but not sufficient basis for defining data accuracy, because calibration of an instrument in a laboratory cannot completely define how well it will operate in the field. For example, a well-calibrated propeller anemometer operated in its stall zone (wind flow within a few degrees of perpendicular to the propeller shaft) will not produce usable data. Functional testing is a method for defining how well instruments perform in the field, and offers the advantage of comparing instruments while they are performing under real atmospheric conditions. Figures of merit used in functional testing are bias, comparability, and precision as defined by Hoehne

(1971) and presented in table 1-1. These figures of merit are used to define performance with respect to an accepted standard instrument exposed to the same conditions. Functional precision, as defined by Hoehne (1977), is the rms difference between readings of two or more instruments of the same design operating in the same environment. Functional precision defines whether differences in readings from two similar instruments are likely to be significant. Differences in instrument readings less than the functional precision are unlikely to be significant. Comparability is an analogous term used when testing instruments of different design.

For practical applications, good operational comparability or functional precision between instruments is a more valuable attribute than precise absolute calibration. Functional testing can be performed in the field using a transfer standard (Lockhart, 1989B), saving instrument downtime. For many meteorological quantities, accurate differences in instrument readings such as wind shears and temperature gradients are more important than absolute accuracy of individual readings. A disadvantage of functional testing is that the tested instruments are rarely exercised over their full operational range. Functional testing, therefore, compliments but does not replace laboratory calibration. On the other hand, functional testing may be the only practical means available to determine the performance of remote-sensing instruments that cannot be operated in a laboratory. Finkelstein et al. (1986) and Hoehne (1977) provide examples of functional testing for in-situ meteorological instruments.

1.3.4 <u>Signal Checks</u>. Installation of calibrated analog signal-generating equipment is followed by end-to-end signal checks prior to test data collection. Signal checks involve application of a known voltage or frequency at the sensor head and monitoring the result at the point where data are logged. Translators often include a voltage-bias adjustment designed to compensate for system bias. Alternatively, the signal can be logged with its known bias and subjected to later software corrections. Slow drift in signal bias because of grounding changes can be identified by periodically repeating end-to-end checks or performing these checks when significant changes in the electromagnetic environment are suspected. Instruments that provide a shielded digital output are less susceptible to signal corruption. Interference large enough to affect the signal usually causes data loss.

1.4 Relevance

Relevance is the first and final consideration in a QC program. Unlike validity, relevance is often a qualitative rather than a quantitative matter that requires application of judgment and communication skills as well as technical knowledge. Establishment of a relevant measurement program begins with an

understanding of program objectives followed by selection of adequately exposed instrument sites, the use of appropriate sampling and averaging times, and the timely dissemination of the required information in a usable format.

1.4.1 Measurement Program Planning. Relevance is particularly difficult to achieve for the Mission Support Process, because data must be quickly gathered and transformed into information without the benefit of post-test analysis. It is very important that the range meteorologist interact with the project directors early in the mission planning stage to define meaningful and achievable measurement goals and to identify mission meteorological limitations. Regulatory agencies are also showing increasing interest in measurement relevance, particularly in the air quality area. Hoffnagle et al. (1981), for example, define relevant instrumentation and information requirements to characterize diffusion from point sources.

1.4.2 Site Selection and Instrument Exposure. Site selection is an important aspect of relevance for meteorological measurements. To provide representative data, instruments must be mounted in an environment where they can perform according to their design specifications. Functional testing can help determine which instruments can, in a given setting, provide the most representative data. The site chosen for measurement must adequately expose the instrument to the phenomenon to be measured. The site must also be one where the instrument is not likely to suffer damage or tampering. Site selection in flat, isolated, open terrain is not difficult, but difficulties increase in the presence of complex terrain and manmade obstacles. If sensor exposure is compromised by other operational constraints, a description of the problem and its anticipated effects should accompany data obtained from the site.

Instrument exposure can be defined in terms of fetch, which is the distance upwind from a measurement site to the nearest discontinuity or obstacle that is likely to influence instrument readings. Wind measurements are the most susceptible to exposure problems. For wind readings, a fetch to obstacle height ratio of at least 15:1 is needed to obtain undisturbed wind profiles (Wieringa, 1976). The measurement site should also be at least 150 meters from any discontinuity in site roughness. To obtain representative measurements above a surface, an anemometer should be mounted at a height at least five times the surface roughness length above the surface. The long-term correlation between wind speed and wind direction should be at its maximum along the prevailing wind direction for a properly exposed anemometer stationed in flat, open terrain. A persistent correlation between wind speed and direction that is unexplained by the prevailing winds can provide a quantitative measure of the terrain or obstacle influence on wind measurements. Quantitative measures of persistence and correlation are described in chapter 3, paragraph 3.2. A detailed discussion of roughness, fetch, and rules for matching a measurement array to the available terrain is presented by Wieringa (1993). Equipment siting guidance can be

obtained from the manufacturer, from a command technical assistance office, or from a standards-writing organization such as the American Society for Testing and Materials (ASTM).

1.4.3 Sampling and Averaging. To produce relevant information, measurements must be made using instruments with suitable response characteristics and appropriate sampling rates. Instrument response is usually defined in terms of a time or distance constant. This response characteristic should exceed, by a factor of 10 or greater, the scale or duration of the least significant event to be measured. The sampling rate should be comparable with the instrument's response. For example, there is little to be gained by sampling once per second or trying to resolve features of less than 2-minutes duration using a thermometer with a 12-second response time. Choosing an instrument with response characteristics and a sampling rate consistent with the anticipated measurement requirements maximizes the available information content while minimizing measurement redundancy.

Averaging time should be a function of application and atmospheric conditions. Data collected within a specified averaging time are used to produce statistics; these statistics constitute the information needed to evaluate the data and model the phenomenon of interest. Averaging should be avoided over periods when major trends or step changes are present in the data.

The choice of an averaging period is also dependent on sampling rate and the statistics of interest. First-moment statistics (means) require fewer data points to produce reliable estimates than do second-moment statistics (variances). For example, given an anemometer and vane sampling at a rate of 1 Hz, 1-minute averaging may be sufficient to define a mean wind, but 15 minutes of data may be required to define wind-direction variance with an acceptable level of statistical significance. Lenschow et al. (1994) provide guidance on choosing suitable averaging times and present a methodology for defining random versus systematic errors in turbulence statistics.

While sufficiently long averaging periods are needed, excessively long averaging times and large sample sizes should be avoided. Wind direction averaging in excess of 1 hour may include undesired long-term trends. The effects of trends can be minimized through the use of detrending (high-pass filter) algorithms. Detrending is particularly important for spectrum analysis (see chapter 4, paragraph 4.5). Conversely, unnecessary high frequency data or random noise can be suppressed through block averaging or low-pass filters. Block averaging produces independent samples, while running-mean and median filters provide smoother point-to-point transitions.

1.4.4 <u>Information Dissemination</u>. Computers are invaluable aids in the data collection, analysis, display, and archival processes, but with this additional speed and processing capability comes the expectation that data will be made available quickly. Data should not be disseminated without quality control. Rapid dissemination of dubious or irrelevant data is not in the best interest of range customers. A statement of quality and an explanation of QC procedures used should accompany all disseminated information. A review by a meteorologist with knowledge of mission objectives and information requirements and a firm understanding of meteorological processes remains the key to a successful measurement program.

Data that are meant to be shared with other users should be presented, if possible, in ASCII format. A multitude of media are available for archiving data, but a 9-track tape remains the only medium that is common to all member ranges for the transfer of large quantities (tens of megabytes or more) of data, although compact discs (CD-ROM) are emerging as a common mass-storage medium. Applications of CD-ROM in the atmospheric sciences are discussed by Mass (1993). For smaller quantities of data, floppy disks are inexpensive and convenient and can be read at most ranges. Data compression enhances the storage capacity of floppy disks. The 3½-inch disks are more robust and generally survive transportation better than 5¼-inch disks.

Data formats must include a certain minimum amount of documentary information to be of value to anyone other than the immediate user. This minimum information includes station identification, a date/time stamp, the sampling rate and averaging interval, sensor height above ground, sensor location, and measure units. Data sets intended for future use should also include documentation on instrument type, axis orientation (as applicable), data corrections or adjustments, sampling interval, project name, and data quality indicators. Additional test information should include a site description consisting of roughness elements, obstacles, major terrain features, and the probable effects of these features on the data such as wake effects for certain wind directions. Data presentation should be clear and in standard meter-kilogram-second (mks) units unless the use of alternative units is coordinated with customers. Standard mks units are presented in <u>Practice for Use of the International System of Units (SI) (the Modernized Metric System)</u> (ASTM E380). Time is preferably presented in Universal Coordinated Time (UTC). Local standard time (LST) is acceptable for data sets designed primarily for local use. Time stamps should indicate whether UTC or LST is used. For data averaged over time, the time stamp is usually taken at the beginning of the averaging period. If an alternative convention is used, that convention should be noted in the data set.

Hard-copy data summaries are more meaningful when presented in a format designed for user interpretation. For example, wind speeds and directions from a given station are most useful when presented in adjacent columns and in clearly defined, common units. The same is usually true for temperatures and dew points. Exceptions are made for some applications. On a multilevel tower, wind speeds and temperatures may be best presented in an adjacent column format when the gradients of these variables are of primary interest. Tabular formats are most easily read when there is sufficient separation (at least two spaces) between columns. The number of significant digits should not exceed the resolution of measurements. For example, wind speed and temperature are likely to be significant to a tenth of a unit, while wind direction is likely to be significant to the nearest whole degree. Obtaining customer input on desired presentation formats before measurements are taken can save time and improve customer satisfaction.

CHAPTER 2

ERROR SOURCES

2.1 Missing Data

Because an "open line" or "short" can sometimes be confused with a valid zero or full-scale voltage reading when using analog instruments, a method to uniquely identify the condition when no data are present is a concern. Zero or full-scale voltages are easier to identify before conversion to their equivalent in engineering units. Likewise, a single bad-data point is usually easier to identify before it is averaged with other data points. It is, therefore, desirable to perform checks for open line or short conditions early in the QC process before averaging or conversion to engineering units. For anemometers, 0 to 5 volts might convert to a speed range of 0.2 to 50 meters per second (m/s). Alternatively, if the voltage range is -5 to +5 volts, zero volts may produce a reading of 25 m/s. For a thermometer, 0 volt is often set for the lowest temperature of the operating range, producing a reading of -49.9 °C, while full scale is equivalent to 50 °C. Wind direction can be particularly confusing because either 0 or full scale (4.9 volts) might indicate a north wind reading from a sensor with a single potentiometer. Wind direction monitors using dual potentiometers often set the first potentiometer to range between 0 and 270° and the second potentiometer to range between 270 and 540°. Identifying the "no data" condition is a difficult problem, particularly for an automated data-collection system.

Given the difficulty of identifying missing data versus a valid null voltage reading, analysis of multiple sensor records can help identify a missing data condition. For example, a typical mesometeorological network (mesomet) station might report wind speed, wind direction, and temperature. A 0 volt reading may be valid data for one sensor and may even persist for a few hours (calm winds, for example). However, it is unlikely that the atmosphere would produce conditions that register as null voltages simultaneously for two or more sensors on a given station; that is, a persistent north wind of 0.2 m/s or less and a temperature of -49.9 °C is unlikely even if the station is located in the Yukon. For most locations, the simultaneous acquisition of null-voltage data points on two or more sensors at a single mesomet site provides strong evidence of a no-data "open line" condition, particularly if these readings persist over several averaging intervals. Analogous criteria can be used to define a "short" condition. Monitoring an on-site battery reference voltage can be helpful in identifying the existence of a no-data condition at the cost of logging an additional channel of data.

Line noise may also be present to produce some dither (irreducible random noise) or bias voltage even when nothing is coming from a sensor. Thus, line noise may produce the appearance of sensor activity even when an open line or short condition exists. Consequently, it is important to periodically perform zero-voltage checks through the system. If a dither of, say, ±0.01 volt or a bias of +0.02 volt is found, it should be considered in the QC criteria for null data.

Automated procedures should be used to flag suspected null data. If this condition is confirmed by a meteorologist during the QC process, these data points should be assigned a unique character or numerical value that is easily distinguished within the archived data set. The preferred identifier for missing data is a string of 9999. The string should fill all the digits available for any data character (that is, -49.9 becomes 999.9). Alternatively, a special control character can be used to flag suspect data points. The # sign can be used for this purpose (-49.9 becomes -49.9#). The advantage of using a control symbol of this sort is that the analyst can observe each reported value and add or remove control symbols as deemed necessary; data-processing routines can be programmed to ignore numerical values followed by a # sign.

An open line or short condition is less likely to be confused with real data for digital instruments because the transmitted character is a string of 0 or 1. Digital transmission is also done in a specific message format that precludes confusion with an open line or short condition. Received data packets can be subjected to format (check sum) and parity checks that unambiguously identify gross-error conditions. In this respect, some basic QC is already built into digital instrumentation. On the other hand, the digitally transmitted signal may include pre-averaged data in which noise or short conditions are already averaged into the transmitted signal, creating a very difficult QC problem.

2.2 Noisy Communications Lines or Acquisition System

Analog output-voltage signals are susceptible to contamination during transmission from the sensor to the point where data averaging and storage are performed. Analog data typically originate as voltage or current signals from the sensor head and pass along a wire to a translator that amplifies and conditions the signal, which is then passed to a data-logging device.

Communications lines, particularly metal cables, present many opportunities for signal corruption. Cable resistivity causes a voltage loss, imposing a bias on the signal. All electrical systems are referenced to ground and are susceptible to grounding changes because of variations in soil moisture content. Moisture penetration into the cable sheath may also impose variable voltage offsets. Cables also act as antennas, receiving inductance from other nearby cables, particularly power cables, and are susceptible to changes in the atmospheric electric field.

Some of these conditions can be identified and corrected through end-to-end signal checks, but others are variable and must be minimized through careful grounding and cabling practices.

Good grounding and cabling practices are necessary for the acquisition of analog data free of noise and bias. Signal cables should never lie parallel to power cables or in long runs next to other signal cables, particularly when they are poorly shielded. When it is necessary to have cables near each other, they should be shielded. Cabling should be laid out to cross at right angles to minimize inductance. Also, common and stable grounding should be established for all equipment on a tower. If possible, this grounding should be common with the data acquisition system. If common grounding is not achieved, ground loop voltages may pass through the system. Grounding and ground loop conditions often vary with changes in soil moisture.

Translators, signal conditioners, and amplifiers contribute a certain amount of background noise and bias to an analog signal. The signal at this point is also susceptible to field effects because of radio transmitters or other nearby sources. Radio transmitters, when keyed, can produce data spikes. Electronic interference checks should be done by systematically turning on or keying equipment while watching for signal output level changes in the data monitoring system.

Signals transmitted as frequency counts or in digital form are less subject to noise and interference than are voltages. Wind speed signals, often transmitted as pulses, are less susceptible to errors caused by grounding and cabling faults than wind direction voltages. Digital signal quality is also insensitive to small changes in voltage level and is less susceptible to these errors.

2.3 Environmental Hazards

In addition to electromagnetic hazards, the biological and meteorological environment creates special hazards for meteorological equipment, particularly for equipment left in the field for extended periods. Insects build nests or webs in exposed housings, air intake ducts, sunshades, and electronics shelters with openings. The first indication of a problem may come as an intermittent "open" or "short" in the signal, but the instrument can experience slow degradation of signal quality well before a fault is detected. Rodents are known to chew cables and burrow under or into standing shelters. Birds perch on wind vanes bending the arms and attack rotating instruments such as cup anemometers.

Sites with known biological hazards will require special attention such as sealing electronics housings and designing equipment mounts to make animal access difficult or unattractive. Installing a bird perch above wind equipment can reduce the incidence of bent wind vanes. Cup anemometers that strongly reflect

sunlight seem to provoke attack by raptors, and many insects are attracted to the color yellow. Choosing colors, coatings, and configurations that do not provoke or attract birds or insects can help minimize damage. Cabling at a permanent site can be buried, although the caution against long runs of closely laid parallel cable remains. Cabling lying on the ground is susceptible to gnawing by rodents. Mounting cables on poles above the ground may provide adequate cable separation, but cable coverings should be designed to withstand damage caused by wind loading and degradation by ultraviolet radiation.

Meteorological effects include sensor degradation caused by intrusion or accumulation of moisture, salt, dust, mud, or ice and damage from overheating or severe weather. Rotating instruments such as mechanical anemometers and wind vanes are particularly susceptible to these effects. Salt accumulation is prevalent in the marine environment where sea spray leaves a deposit on instruments. In dry environments, fine dust can filter into electronics components and bearing assemblies, and long-term exposure to intense ultraviolet radiation causes plastic or composite components to become brittle and crack. Mud splatter during heavy precipitation events can coat instruments and block aspirators or cooling vents. Ice in the form of rime or snow can accumulate on sensors, and ice in the form of hail and strong winds can physically damage instrumentation.

Humidity is a major environmental hazard for instrumentation. Condensation in high humidity conditions can cause electronics faults or distortion on optical surfaces. Mold and fungi can also grow on damp surfaces, degrading signal strength or reducing sensitivity. Growth often begins on shields or shelters and may go undetected until noticeable instrument performance degradation occurs. Very low humidity is accompanied by increased static electricity which can damage electronics or cause dust to accumulate on sensors or optical surfaces.

Environmental hazards impact the quality of meteorological data in a variety of ways, depending on the sensor. Cup or propeller anemometers may cease to turn after receiving deposited material, or may break free of the material only with the passage of a sudden gust of wind. Accumulations of foreign matter can also alter an instrument's aerodynamic characteristics, thereby degrading its threshold and response distance. On nonmechanical instruments, these hazards can appear as signal loss, bias, or noise because of ventilation duct blockage or obscuration of the path between an optical transmitter/receiver pair.

Adverse meteorological effects on data quality can be minimized through careful selection of equipment designed for use in adverse environments. Ice accumulation can be minimized by using heater elements and by covering sensor surfaces with a hydrophobic coating. Frequent cleaning for sea spray or dust and special site visits after storms may be necessary to keep instruments in good operating condition.

2.4 Alignment Errors

Alignment accuracy is particularly important for wind-measurement equipment. Anemometers not vertically aligned will exhibit unusual acceleration characteristics (MacCready, 1966). A wind-vane alignment error appears as a bias in the wind direction measurements. Mechanical-wind equipment should be aligned to within ±2° of vertical to minimize measurement bias from off-axis winds. Instruments set up to measure alongwind (u), crosswind (v), and vertical wind (w) components also require careful alignment (to within ±0.1°) for stress measurements (Kaimal and Haugen, 1969). Cross-component contamination caused by misalignment is difficult to remove. Vertical velocity, usually a small fraction of the horizontal wind, is particularly susceptible to cross-component contamination.

Alignment with respect to either magnetic north or true north is acceptable, but this alignment choice must be clearly stated. Wind direction is usually reported with respect to true north, so instruments aligned with respect to magnetic north will need to have a software correction applied to the angular information unless the magnetic declination is zero. Magnetic declination information presented as a diagram of the relationship between grid north, true north, and magnetic north, can be found on U.S. Geological Survey or Defense Mapping Agency maps. The declination angle varies slowly with time because of changes in the magnetic pole, so the use of fairly recent maps (within the last 20 years) and the yearly correction (also annotated on these maps) is recommended. If the magnetic north pointer is east (west) of true north, add (subtract) the magnetic declination to (from) the magnetic north wind reading to get a wind reading with respect to true north. Alignment accuracy should be within ±2°. Lockhart (1989A) provides a methodology for obtaining a precise alignment using the true solar-noon method.

2.5 Calibration Inadequacies

Static and dynamic calibrations are used on instruments with analog output. Static calibration usually involves mounting an instrument in a test fixture and checking voltage output at a series of predetermined positions. Static calibrations check the validity of algorithms used to convert voltages to engineering units over the operating span but provide no information on the dynamic performance of the instrument. Static calibration is adequate for instruments measuring thermodynamic quantities such as temperature, pressure, or humidity but is insufficient for the calibration of rotating wind speed and direction equipment. Rotating-wind equipment require both mechanical and electrical checks. When calibrations are done, electrical circuitry designed to dampen signals (usually resistor capacitor (RC) filters) should be bypassed so that the true electromechanical instrument response is measured.

Dynamic calibration should be performed in a wind tunnel where anemometer and wind-vane performance can be defined with respect to steady-state flow conditions. Dynamic measures include the threshold, which is the lowest speed at which a rotating anemometer starts and continues to turn, or a vane which starts to turn towards the true wind direction from an initial displacement of 10°. The threshold should be checked periodically by the user, because it is a sensitive indicator of bearing degradation. Other dynamic measures for wind vanes include delay distance, damping ratio, and overshoot as defined by ASTM-D5096 (1990) and Lockhart (1989A). Performance and calibration specifications should be provided by the manufacturer.

Although the dynamic performance of wind equipment is defined in a low-turbulence wind tunnel, its actual performance in a turbulent-wind field is another matter. Mechanical wind equipment is calibrated after having the opportunity to come into equilibrium with the tunnel's velocity field. If subjected to atmospheric turbulence at scales comparable to or greater than the distance constant (L), the sensor cannot approach equilibrium and will provide an attenuated wind reading. A rotating anemometer exposed to a step change in wind speed (Δu) over a time period (t) will report an attenuated fraction (A) of the Δu expressed by

$$A = [1 + (2\pi L/\Delta u t)^2]^{-0.5} \tag{2-1}$$

Therefore, wind equipment with a large-distance constant, even if well calibrated, cannot provide representative wind measurements near the surface or in locations where gusty conditions are prevalent. Near-surface wind measurements require fast-response sensors, while heavier slow-response sensors are more appropriate for wind measurements at greater heights where stronger but less turbulent wind conditions occur.

In addition to providing current calibrations for equipment, calibration facilities should report the calibration errors found when an instrument entered the facility. These errors can then be used to correct data collected by the equipment prior to recalibration. Also, the record of calibration errors can be used to define a calibration schedule. Instruments that consistently exhibit no calibration drift can be put on a longer calibration interval, while instruments that consistently exhibit significant calibration drift should be returned to the calibration facility sooner (MIL-STD 45622A, 1980).

2.6 Time Synchronization

Time synchronization is necessary for all meteorological measurements, and time should be part of any measurement record. Time-accuracy requirements vary with the application. Accuracy to within a minute is adequate for synoptic applications, but accuracy to within a tenth of a second is needed if the recorded data are to be used for flux computations. Computer-system time is often derived from the 60-Hz signal passing through the power supply. A more adequate time base is obtained by reference to IRIG timing or to a GPS-satellite time base. The reference time system being used should be identified. Universal Coordinated Time (UTC) is the preferred clock time, especially for data that are to be used off range. If UTC is not chosen for on-range applications, local-standard time is recommended for use throughout the year.

CHAPTER 3

REAL-TIME QUALITY CONTROL

3.1 Operational Quality Control Checks

Operational quality control checks to monitor data quality include those actions that can be taken during or shortly after data collection. These actions include using one's knowledge of the measurement system and the measured geophysical phenomena during inspection of the data and summary statistics, and using real-time predictors to flag possible fault conditions. Steps in the QC process are outlined briefly below.

3.1.1 Become familiar with instrument and data-system performance characteristics, error modes, and tolerances. Much data are lost because the operator does not understand equipment capabilities and limitations. Each instrument has characteristic error modes that a well-trained analyst should be able to identify during a review of the data.

3.1.2 Perform out-of-range and gross departure checks as close to the measurement source as possible. Errors masked by averaging or conversion into derived variables are more difficult to detect and cause more information loss than errors detected early in the measurement process.

3.1.3 Use known physical relationships to check measurement validity. Flag gross departures from the hydrostatic condition, the adiabatic lapse rate, or large step changes in signal level. These conditions represent either an emerging fault or the onset of an interesting meteorological condition. In either case, these conditions warrant further attention.

3.1.4 Use intersensor and intervariable comparisons. Changes in one measured field are often accompanied by changes in another. For example, a change in pressure should be accompanied by a change in the wind field. A major change in one variable without an accompanying change in related variables may be due to the emergence of an error or fault condition.

3.1.5 Plot time-series of the data for visual inspection. Plotted data can be quickly scanned for trends, spikes, or flat response conditions. If possible, plots should encompass one or more meaningful cycles such as the diurnal heating cycle. Profile plots can be quickly scanned for faults. For example, figure 3.1 contains a profile of four unedited v-component (crosswind axis) sonic anemometer data sets collected simultaneously at a rate of 5 Hz over a period of 1 hour (18,000

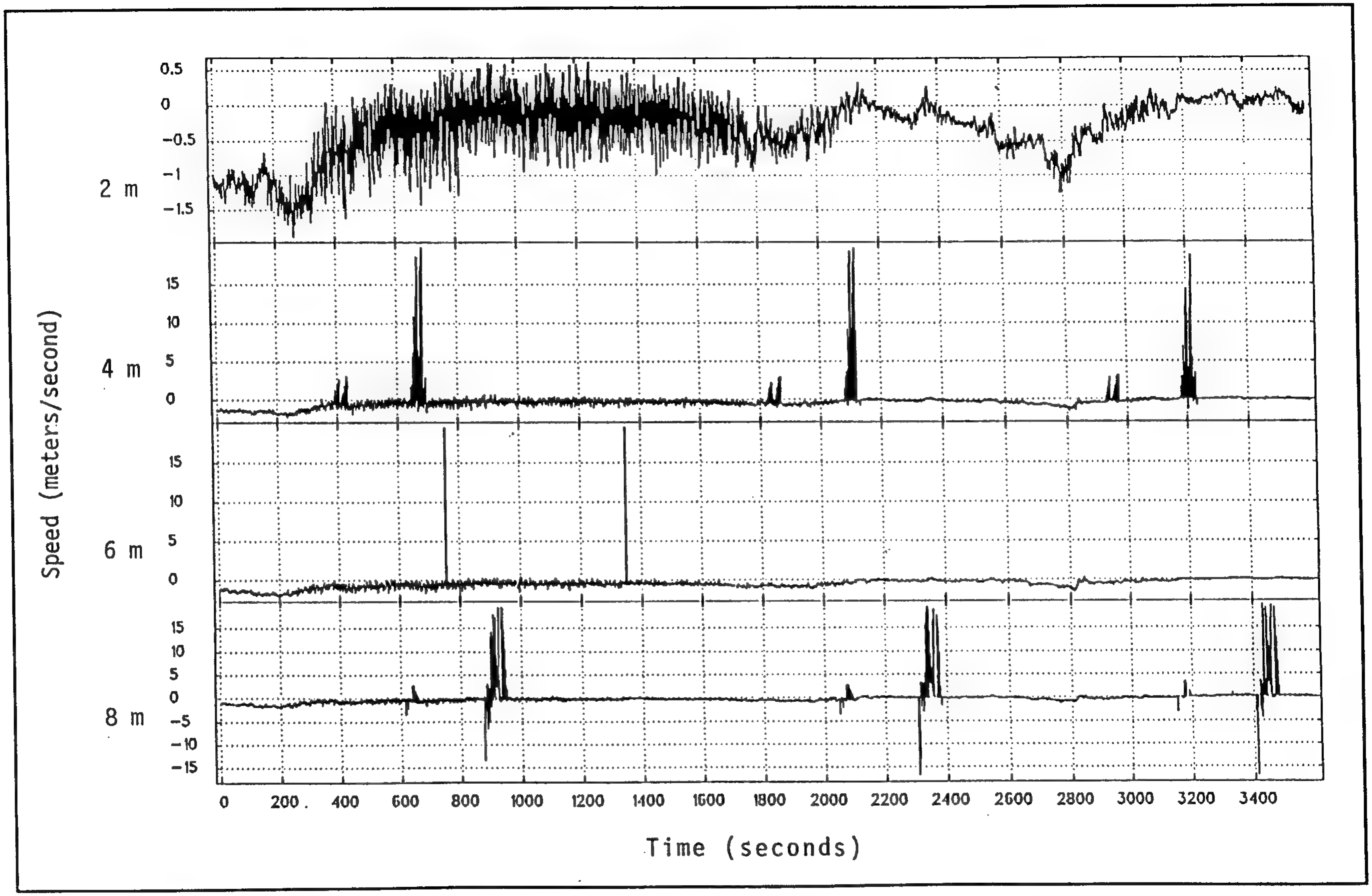

Figure 3-1. Unedited v-component sonic anemometer time series data from instruments mounted at the 2-, 4-, 6-, and 8-meter levels on a tower. (Note: Each panel is auto-scaled.)

data points in each set). The top panel is the v-component measured at the 2-meter level on a meteorological tower, while the lower panels show the v-components measured respectively at 4-, 6-, and 8-meter on the same tower. A quick visual inspection reveals clusters of noise spikes at the 4- and 8- meter levels, and two isolated spikes on the 6-meter level.

3.1.6 Calculate summary statistics over meaningful averaging periods. Choice of a meaningful averaging period depends on the time scale of the phenomenon of interest but should include at least 250 data points for calculation of a standard deviation. The basic summary statistics (the mean, median, maximum, minimum, and standard deviation) calculated for this averaging period can be good indicators of the presence (or absence) of noise.

3.1.7 Use the last measured data point and a running mean of 10 to 100 data points as a real-time predictor for each new data point. Significant deviations from the predicted value can indicate either the emergence of a fault condition or a change in meteorological conditions.

3.2 Meteorological Variables Basic Statistics

Meteorological variables consist of scalar quantities such as temperature and humidity and vector quantities representing the wind. Basic statistics for scalar quantities can be computed using methods presented in statistics texts. Wind data can be presented as components (eastings and northings) or as speed and direction. The treatment of wind requires special care because of the discontinuity in the wind direction circular scale between 360° and 001° and because of possible ambiguity in the quadrant representation of the arctangent function. Also, the choice of algorithm (for example, scalar or unit vector) will bias the outcome. Algorithm selection should be based on how the wind data are to be used. A scalar-averaged wind speed, unit vector-averaged wind direction, and circular standard deviation are appropriate for most applications. The remainder of paragraph 3.2 contains computationally efficient single-pass algorithms for computation of scalar or vector quantities. Table 3-1 shows sonic anemometer-derived summary statistics obtained by using many of these algorithms.

3.2.1 Scalar Mean. For n samples of a scalar quantity α, the mean $(\bar{\alpha})$ is the sum of the samples divided by n.

$$\bar{\alpha} = \frac{1}{n}\left(\sum_{i=1}^{n} \alpha_i\right) \tag{3-1}$$

If the quantity to be computed is a scalar mean horizontal wind speed $(\overline{ws})$ obtained from along-axis (u-component) and cross-axis (v-component) measurements, the mean is the sum of the squares of each individual velocity component.

$$\overline{ws} = \frac{1}{n}\left(\sum_{i=1}^{n} [u_i^2 + v_i^2]^{0.5}\right) \tag{3-2}$$

3.2.2 Vector Mean Speed. The horizontal vector mean wind speed $(\overline{wv})$ is the square root of the sum of the squares of the mean alongaxis $\bar{u}$ and crossaxis $(\bar{v})$ horizontal velocity components.

$$\overline{wv} = \frac{1}{n}(\overline{u}^2 + \overline{v}^2)^{0.5} \tag{3-3}$$

NOTE: The vector mean wind speed is applicable to calculation of atmospheric transport for diffusing clouds. The scalar mean wind speed is the variable of choice for most other applications. A ratio of the vector to scalar wind speeds is a measure of wind direction persistence (Panofsky and Brier, 1965).

3.2.3 Unit Vector Mean Direction. For a set of wind direction angle (θ_i) observations, the unit vector mean wind direction $(\bar{\theta})$ is obtained from the arctangent of the averaged sines (E) and cosines (N) of the wind direction angles

$$E = \frac{-1}{n}\sum_{i=1}^{n} \sin\theta; \tag{3-4}$$

$$N = \frac{-1}{n}\sum_{i=1}^{n} \cos\theta; \tag{3-5}$$

$$\theta' = \arctan\,(N/E) \tag{3-6}$$

To ensure that the resultant falls within the correct wind direction quadrant,

$$\bar{\theta} = \begin{Bmatrix} 90 - \theta', & E<o \\ 270 - \theta', & E>o \end{Bmatrix} \tag{3-7}$$

NOTE: The negative signs in equations (3-4) and (3-5) are used to achieve the standard meteorological convention with wind directions from the west and south having a positive sign.

3.2.4 Speed-Weighted Mean Direction. The wind speed-weighted mean wind direction includes the set of wind speed (S_i) in the computation of sines and cosines,

$$N_v = \frac{-1}{n} \sum_{i=1}^{n} S_i \cos\theta i \tag{3-8}$$

$$E_v = \frac{-1}{n} \sum_{i=1}^{n} S_i \sin\theta i \tag{3-9}$$

and processing the resulting components through equations (3-6) and (3-7). NOTE: The degree to which the unit vector and speed-weighted mean directions agree is a measure of the lack of correlation between fluctuations of wind speed and direction (Yamartino, 1984).

3.2.5 Scalar Standard Deviation. For n samples of a scalar quantity α, the standard deviation σ_α (Panofsky and Brier, 1965) is

$$\sigma_\alpha = \left(\frac{1}{n} \sum_{i=1}^{n} \alpha_i^2 - \bar{\alpha}^2 \right)^{0.5} \tag{3-10}$$

where $\bar{\alpha}$ is as defined in equation (3-1).

3.2.6 Persistence Estimator of Standard Deviation. An estimate of the wind angle standard deviation σ_θ can be obtained using persistence defined as the ratio of the scalar to vector mean wind speeds as defined by equations (3-2) and (3-3) (Weber, 1991).

$$\sigma_\theta = 105.75 \left[1 - \left(\frac{wv}{ws}\right)\right]^{.5337} \qquad (3\text{-}11)$$

NOTE: This method can provide a σ_θ estimate using wind component data when direct wind direction measurements are unavailable.

3.2.7 Circular Standard Deviation. The standard-deviation estimator that produces the least error (±2°) for computation of the circular wind direction standard deviation (σ_θ) over an angular range of 0° to 103.9° (Yamartino, 1984) is

$$\sigma_\theta = \arcsin(\epsilon)\,[1 - 0.1547\,\epsilon^3] \qquad (3\text{-}12)$$

where

$$\epsilon = 1 - (E^2 + N^2). \qquad (3\text{-}13)$$

3.2.8 Covariance and Correlation. A covariance (Cov) is the product of two time-dependent quantities. For quantities A(t) and B(t) with means of $\bar{A}$ and $\bar{B}$

$$Cov = \langle[A(t) - \bar{A}]\,[B(t) - \bar{B}]\rangle, \qquad (3\text{-}14)$$

where < > indicates a user-selected time average. Covariance normalized by the variances of the time-dependent quantities (σ_A^2, σ_B^2) gives the coefficient of correlation (Cor) between these quantities

$$Cor = \frac{\langle[A(t) - \bar{A}]\,[B(t) - \bar{B}]\rangle}{[(\sigma_A^2)\,(\sigma_B^2)]^{0.5}} \qquad (3\text{-}15)$$

TABLE 3-1. A STATISTICAL SUMMARY OBTAINED FROM 3-AXIS SONIC ANEMOMETER DATA TO INCLUDE MEAN WIND COMPONENTS, VARIANCES, STANDARD DEVIATIONS, TURBULENCE INTENSITIES, AND COVARIANCES.

Date: 28 Feb 1994
Trial Nr.: a59730
Sonic Loc.: 1.8 m tri-axis

Time: 0730 MST
Location: West Tower
Axis Orient.: 180° (True)

A. MEAN VALUES

START TIME HR:MIN:SEC	SCALAR SPEED M/S	VECTOR SPEED M/S	WIND DIR DEG	ALONG AXIS M/S	CROSS AXIS M/S	VERTICAL WIND M/S
07:30:00:	0.4	0.3	64.2	-0.125	0.259	-0.02

B. VARIANCES

START TIME HR:MIN:SEC	U'U' M^2/S^2	V'V' M^2/S^2	W'W' M^2/S^2	Ts'Ts' $DEGK^2$	REJECTED DATA POINTS	SPEED OF SOUND M/S
07:30:00	0.112	0.055	0.025	0.044	0	336.6

C. STANDARD DEVIATIONS (Rotated)

START TIME HR:MIN:SEC	SIGMA U M/S	SIGMA V M/S	SIGMA W M/S	SIGMA Ts DEG	SIGMA THETA DEG
07:30:00	0.335	0.235	0.159	0.211	ND

D. TURBULENCE INTENSITIES (RADIANS)

START TIME HR:MIN:SEC	LONG Ix	LATERAL Iy	VERTICAL Iz
07:30:00	1.164	0.818	0.554

E. COVARIANCES (Rotated)

START TIME HR:MIN:SEC	U'V' M^2/S^2	U'W' M^2/S^2	W'Ts' MDegK/S	U'Ts' MDegK/S
07:30:00	-0.0005	-0.0171	0.0088	-0.0334

3.3 Sampling and Representativeness

All of the measurements needed to completely describe the phenomenon of interest are rarely available; consequently, the true-population statistics are never absolutely known. However, if a sufficient number of measurements are taken, it is possible to form acceptable estimates of the means, variances, and other population statistics. For a statistically stationary process, it is possible to determine the number of random independent samples needed to estimate the process population statistics to within a specified degree of precision and statistical significance. The number of samples required varies roughly with the inverse of the square of the required precision. Procedures for calculating the precision and significance are available in any number of statistics texts. Lenschow et al. (1994) provide a statistical significance calculation procedure adapted for atmospheric measurements.

The difficulties in applying standard statistical procedures to meteorological time series data are that meteorological processes are seldom stationary, and sequential samples taken from a time series are neither random nor statistically independent. Judgment on the part of the analyst is needed to overcome the first problem. Means or standard deviations calculated from a data set obtained during a significant trend or transition may be mathematically correct but functionally unrepresentative. For example, a mean wind direction measured during a wind shift will not represent the prevailing conditions before or after that event, and the standard deviation of these measurements will be excessively large. A procedure for estimating statistical independence is described below.

The net effect of sequential sampling from a time series where persistence occurs on time scales greater than the sampling interval is that the effective (statistically independent) sample size (n) is less than the number of data points measured (m). A measure of persistence (Ra) given by Brooks and Carruthers (1953) is

$$Ra = \frac{\sigma\sqrt{2}}{\sigma_d} - 1, \tag{3-16}$$

where σ is the standard deviation of a data set and σ_d is the standard deviation of the differences obtained from one observation to the next within the data set. If the data are from a random series, σ_d should approach $\sigma\sqrt{2}$ and Ra should approach zero. An estimate of n can be obtained by dividing m by ($|Ra|$ +1), where $|Ra|$ denotes the absolute value of Ra.

3.4 Real-Time Predictors

Predictor programs that forecast the next data point in a time sequence based on past data points can be useful real-time QC tools. Predictors are based on the premise that time-sequenced meteorological conditions follow trends and that each data point is correlated to its near neighbors. A combination of the mean of neighboring data points (the local mean) and the last valid measured data point are reasonable estimates for the next data point in a time series. Predictor programs use this estimate to create a forecast of this data point. Each new data point is then compared to the predicted value. If the new data point is within bounds (within upper and lower departure limits of the predicted value), it is accepted without qualification. If the new data point is out of bounds, it is flagged. The flags draw the attention of an analyst who must then decide whether each out-of-bounds data point represents a significant change in meteorological conditions or the emergence of an instrument fault condition. For variables that are expected to change slowly with time (pressure, for example), most of the weighting may be on the running mean. For less conservative variables (wind speed, for example), more weight may be on the latest recorded wind speed. Weighting schemes and departure limits require "tuning" for each site and measured variable to minimize the false-alarm rate.

Hojstrup (1993) describes several real-time statistical predictor models that work well on data distributions that are near-Gaussian. Difficulties arise with this technique when the characteristics of the time series change. An adaptive discrimination factor can be used at the expense of additional computational complexity. This screening procedure is also useful for off-line quality control where the analyst has an opportunity to tune the predictor to the data set.

CHAPTER 4

POST-PROCESSING QUALITY CONTROL

4.1 Post-Processing Steps

Post processing can include a number of analytical and statistical procedures that are too computationally demanding or time consuming for use in real-time QC. Post-processing steps can include the use of despikers to identify out-of-tolerance data points, interpolators to fill in missing data points, objective analysis of the data field, spectrum analysis to define the contributions to variance by different frequency intervals, and smoothers that present general trends without high frequency content. Post processing is generally necessary to transform data into information that can be used to model desired phenomena. Each post-processing step affects the information content of a data set and should be done with a clear understanding of how the derived information is to be used. The range customer should be provided with a description of the post-processing steps taken, the rationale for using each procedure, and the likely effect on the data set.

4.2 Despikers

Noise can be caused by power surges, radio-frequency interference, random-bit errors during data transmission, or by loose or failing connections or components within the sensor or transmitter. These problems may cause impulse noise or spikes. Spikes are often (but not always) randomly distributed, can be of either sign, and are usually of short duration and characterized by rapid rise and fall times.

4.2.1 Central-Tendency Measures. Spikes are usually seen as departures from the central tendency of the majority of points within a data set. Therefore, the most obvious way to identify spikes is to compare each data point to a measure of central tendency. Visually identifiable spikes depart from central tendency by some user-defined criterion such as 3 standard deviations beyond the mean. The QC analyst should try to understand the reasons spikes may be present and how they are distributed within the data before trying to remove those spikes.

Spikes that are clustered or grouped present a much more difficult QC problem than those that are randomly distributed through a data set. Filter lengths must be carefully chosen to exceed the length of any spike cluster. Despikers work reasonably well when spikes are clearly distinguishable from valid readings, when the number of spikes is 10 percent or less of the total data set, and

when the spikes are not clustered. Clustered spikes present a special problem because an adaptive filter can adjust to the spike cluster and begin flagging valid data points. Discrimination between an abrupt shift in valid data and the emergence of clustered spikes is one of the most difficult QC problems. Some degree of manual intervention by the analyst will likely be required.

The available measures of central tendency are the mean, median, and mode. The mean, or average, is the most familiar and the most frequently used for data processing, because it is easy to compute. The median, representing the 50th percentile point in a distribution, is less common because it requires a sorting procedure that is more computationally intensive than computation of the mean. The mode, the most frequently observed data point value in the data set, is a useful measure of central tendency if the magnitude of the true central tendency (or, conversely, the magnitude of the spike) is constant over the sampling period. Mode-based arguments are used to define "consensus" with radar wind profiler data.

4.2.2 Mean Filters. A variety of mean filters are available for identifying spikes in a data set. The simplest of these filters, described in chapter 3, paragraph 3.2, uses the data set maximum, minimum, mean, and standard deviation. A ratio of range to standard deviation is computed. If this ratio is large, indicating the probable presence of spikes, a criterion such as 3 standard deviations beyond the mean is used to flag the spikes. While this simple procedure is useful for means that remain relatively constant, the means in meteorological data often vary greatly with time. A data point in a time series usually exhibits a closer relationship to its near neighbors than to other points that are more distant from it. (Recurring periodic oscillations are exceptions to this generalization.) Therefore, a local or running mean is usually a more effective measure of central tendency for spike detection in time-series data.

Roberts (1993) describes a running-mean filter used by NASA to filter spurious points from time series. A running mean of 100 data points is established at the beginning of each data set with each subsequent data point compared to the mean and standard deviation of the preceding 100 points. (These 100 points are first examined to ensure that they are relatively free of spikes.) If the data point falls within the user-defined criterion (usually within 4 or 5 standard deviations of the mean), the point is accepted into the mean. The filter then steps forward one increment in time, dropping its earliest data point, adding its newly accepted data point, and beginning the process again by recomputing a new mean and standard deviation. Roberts (1993) includes a FORTRAN program for this running-mean filter.

Running-mean filters of the Roberts (1993) design offer an effective methodology for spike identification. It can run through single or multiple passes,

as necessary, to clean up a noisy data set. One disadvantage of this technique is that it is fairly computer intensive, requiring computation of both the mean and standard deviation at each step. Another disadvantage for meteorological data applications is that a large number of data points is needed in the filter (on the order of 100) to compute a statistically stable standard deviation. A simplification of this technique would be to use a standard deviation representative of the whole data set and recompute only the means. This technique will work so long as the standard deviation remains reasonably invariant in time. Alternative running-mean techniques include adaptive-running mean with threshold logic and clipped-mean filters.

An adaptive running-mean filter with threshold logic and dual levels of flagging was developed for meteorological data applications by Biltoft (1993). The adaptive filter adjusts to abrupt changes in signal strength using dual-level flagging threshold logic and a filter reset designed for adjustment to abrupt changes in signal level. Flagging criteria are based on user-chosen levels of departure from the running mean. These departure levels are usually based on a standard deviation estimate. One level of flagging is chosen for easily identified spikes such as data points that are 4 or 5 standard deviations from the running mean. These unconditionally flagged points are excluded from the running-filter mean. The second flagging level, set within the range of the first (2 or 3 standard deviations, for example), conditionally flags a suspect datum. This point is included within the running-mean filter and is re-examined upon exiting the rear of the filter. If, in the meantime, the filter has adjusted to within the accepted range of the datum, the flag is removed and the datum is considered valid. If the filter has not adjusted to within range, the datum retains its flag. Because it does not require continuous standard deviation computations, it is relatively efficient computationally and can use short running-mean filter lengths (10 to 25 points) which are more suitable for highly variable data sets with short autocorrelation times. This technique works reasonably well on noisy data sets as long as spike clusters do not exceed filter-reset length. Results of the application of this filtering technique to the data presented in figure 3-1 is shown in figure 4-1.

Clipped-mean or trimmed-mean filters are running-mean filters formed from a number of data points on either side of the datum in question. A user-selected number (usually 1 or 2) of the highest and lowest values in the set are removed (clipped), and a new mean is computed. If the datum in question is among the points removed, it is flagged or replaced by this mean. If not, the datum is accepted as valid. This technique can be computationally more efficient than the previously mentioned running-mean filter, but it is more susceptible to spike clusters. As the number of clipped points is increased, the clipped mean approaches the median as a limit. Restrepo and Bovik (1988) describe applications of an adaptive trimmed-mean filter for reducing noise in digital signals.

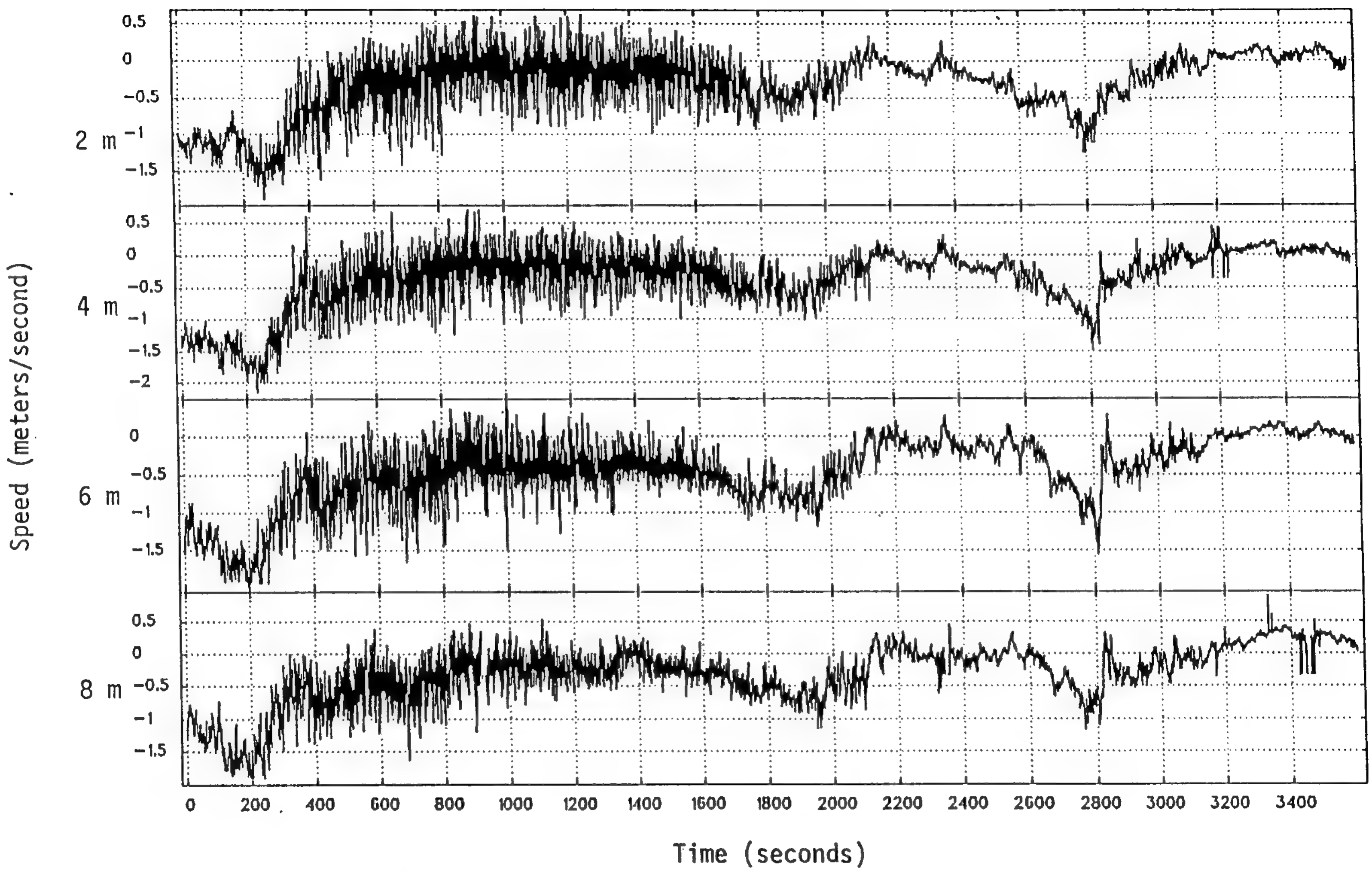

Figure 4-1. **Edited v-component sonic anemometer time series data from instruments mounted at the 2-, 4-, 6-, and 8-meter levels on a tower.**

4.2.3 Median Filters. Median filters provide an effective means of separating signal from noise provided that the filter is large enough to discriminate grouped spikes. Median filters operate by comparing the observed value in the center of a sliding window with the median of data points that form the window. Window length (W) of a median filter is determined by its order (the number of data points, N, on each side of the central point) defined by the relation (Gallager and Wise, 1981).

$$W = 2N + 1 \tag{4-1}$$

A first-order (N=1) filter has a window length of 3 (the center point and data points on each side); a second-order filter has a window length of 5. The choice of N for a median filter is crucial. It cannot discriminate against any pulse or spike cluster whose width is greater than N. Median filters are particularly useful with very noisy data sets as long as N is sufficiently large to discriminate spike clusters. A running median can be less sensitive to noise than a running mean of the same order, because it is influenced by the number but not by the magnitude of noise spikes. However, if the number of spikes sampled exceeds N, the median will represent the spikes rather than the noise-free data. A median filter should track either the valid data or the spikes but (unlike a mean filter) not some average of the two.

Use of threshold logic with a median filter, as described by Brock (1986), requires two passes through the data set. The results of the first pass are used to construct a histogram from the difference values between the data and filter outputs. Spikes appear as lobes in what would otherwise be a normal distribution. The threshold is defined as the minimum on the histogram that separates the normal distribution of "good" data points from lobes caused by spikes. The second pass through the data set targets these lobes. Additional passes can be made, as necessary, to converge on a smoothed signal.

The primary disadvantage of median filters is the computationally demanding sorting needed to define the median. As computer power increases, computational requirements become less of an obstacle. Astola and Campbell (1989) present a fast median-filter computation-algorithm based on a "double heap" process.

4.3 Interpolation Procedures

Interpolation is used to replace bad or missing data points with estimates that closely reflect the real conditions at the time of measurement. Interpolation is not always desirable. It is not necessary if data are to be used simply to

generate summary statistics. However, interpolation may be needed if the data set is to be subjected to spectrum analysis or other complex analyses that require time series with no gaps. Sometimes a "best guess" interpolation is better than an information gap. The customer should be consulted concerning the desirability of using interpolated data.

Simple interpolation for one or two missing sequential data points can be done using the average of the readings before and after the missing datum. This simple procedure is based on the observed autocorrelation within meteorological data. Each data point is more closely related to its immediate neighbors than to points at a greater distance in the time series. The running mean and median filters described in paragraph 4.2 can also be used to fill in missing data points, although these filters produce interpolated values closer to the central tendency. Bednar (1983) describes a procedure where the datum in question is replaced by the median of a sliding window of near-neighbor points. The mean of a data set is unaltered if it is used to fill in missing data points, but this replacement is done at the expense of local data point autocorrelation.

4.4 Objective Analysis

Objective analysis is a procedure used to perform QC on data fields consisting of multiple points in an array. Each datum is compared to its near neighbors. This procedure is particularly useful for networks of surface stations where known physical relationships (the hypsometric equation, for example) can be used to form estimates against which measured values are compared. The end product is a smoothed distribution of values that are mutually consistent with each other and with known physical relationships. Wade (1987) describes an objective analysis technique used on surface mesomet pressure, temperature, humidity, and wind data.

4.5 Spectrum Analysis

Spectrum analysis is perhaps the most powerful tool available for quality control. Fault conditions that are transparent in the time domain are often clearly revealed in the frequency domain. Until recently, Fourier analysis has dominated frequency domain applications; however, wavelet analysis is now also available as a quality control tool.

4.5.1 Fourier Analysis. Measurements made at regular intervals are often presented as time series. Time-series plots such as figure 3-1 and 4-1 representing crossaxis (v-component) wind measurements from four sonic anemometers permit a visual scan of data fields for interesting features and possible faults such as missing data or spikes. Statistical analyses of time series also provide information about the mean, variance, and covariance. Time series analysis alone cannot

describe how the variance of a time-varying quantity is distributed among the various scales of motion that, when combined, form the time series. To better understand atmospheric processes and to eliminate unwanted or erroneous signals, it is often necessary to transform the series from the time domain to the frequency domain where spectral energy is partitioned by frequency rather than by time. Fourier analysis is based on the premise that an extended time series can be decomposed into a linear combination of exponentials that are representable as a spectrum of sinusoidal components. The basic Fourier-based power-spectrum analyses are presented by Blackman and Tukey (1958). For many kinds of geophysical phenomena (the flow of tides, daily or annual temperature change), Fourier analysis can be used to define the most energetic and, therefore, the most important frequencies in a time series and to illustrate details of the interactions between these phenomena.

Fourier analysis of time-series data can provide statistical measures of instrument performance and insight into the physics governing the interactions between sets of time series data. Simple linear correlation and multivariate-analysis procedures are not appropriate for time-series data, because significance tests are based on the hypothesis that the variate samples are uncorrelated. Autocorrelation is nearly always present in the time series of geophysical data. Also, the relationship between two time series can be obscured by an in-phase relationship at some frequencies and an out-of-phase or phase-lagged relationship at other frequencies. Multivariate analyses can be applied to the spectra of a time series after a Fourier transformation of the series from the time domain to the frequency domain. Transformation partitions the power (energy expenditure per unit time) of the time series into harmonic frequency components. For a given variable, "power" is equivalent to the change in that variable per unit time. The total power of the process is equal to the sum of the contributions by the harmonic components. The advantage of power-spectrum analysis over the usual multivariate analysis is that the amount of power contributed by one harmonic is independent of the amplitudes, phases, and frequencies of the other harmonics in the time series. Detailed information on Fourier transform statistical applications is found in texts on time-series analysis (Koopmans, 1974; Jenkins and Watts, 1968); general information on time-series analysis for meteorological data are presented by Stull (1988).

Relationships between two time series can be evaluated by examination of the spectra from the two series and their complex products, the cross spectrum, phase (PHASE), and coherence (COH). The cross spectrum is represented by the cospectrum (COS) and quadrature (QUAD). The cospectrum is analogous to an in-phase covariance between the two spectral frequencies, and the quadrature spectrum is a similar measure phase-shifted ¼ wavelength (90°). The COS and QUAD define the cross-spectrum covariance components in a Cartesian-like coordinate system, while PHASE and COH express these components in a

normalized polar coordinate system. The PHASE, a representation of the angular relationship between two spectra, is defined as

$$PHASE = ATAN2(QUAD/COS), \tag{4-2}$$

where ATAN2 is defined in FORTRAN as the arctangent function expanded to the range $-\pi$ to π. The PHASE is presented in degrees. The COH, the squared coefficient of coherence, is a measure of the correlation between two time series as a function of frequency given by

$$COH = (COS^2 + QUAD^2)/(SPCTR1)*(SPCTR2), \tag{4-3}$$

where SPCTR1 and SPCTR2 are the spectral component magnitudes of time series 1 and 2. The COH is dimensionless and ranges in magnitude from 0 to 1. Statistical significance tests can be applied to coherence data using procedures presented in Koopmans (1974).

A Fast-Fourier transformation (FFT) and spectrum analysis program designed for use with meteorological data is described by Kaimal and Gaynor (1983). The spectra produced by this FFT are smoothed through block averaging, tapered, scaled to meter-kilogram-second (mks) units, and normalized by multiplying each harmonic component by its frequency. For example, table 4.1 presents alongaxis (u-component) wind spectra obtained from sonic anemometers mounted at 0.5- and 1.0-meters above ground level on a tower. Measurements from the sonics were taken concurrently with SPCTR1 representing the 0.5-meter level and SPCTR2 representing the 1.0-meter level. Spectrum band centroid frequencies are presented in the left column, and coherence between the spectrum frequency bands is shown in the right column. Coherence between the 0.5- and 1.0-meter components is high at the lower frequencies (0.019 to 0.063 Hz) but diminishes rapidly at the higher frequencies. Analyses of this type can be used for quality control to locate, by frequency, noise components in a data set.

4.5.2 Wavelet Analysis. Fourier analysis is based on the notion that an infinite time series can be represented in the frequency domain as a spectrum of sinusoidal components of varying frequencies. However, some geophysical phenomena are characterized by intermittent bursts of energy or discontinuities rather than by regular oscillatory motions. Turbulence, for example, occurs as a series of discontinuities in an otherwise quiescent background. On a larger scale,

TABLE 4-1. SONIC TEMPERATURE TIMES SERIES SPECTRA, COSPECTRA, QUADRATURE, AND THE PHASE AND COHERENCE BETWEEN THESE TIME SERIES.

SPECTRA DATA SUMMARY SPECTRAL VALUES						
Frequency HZ	Spectr1 $(T_1'T_1')$	Spectr2 $(T_2'T_2')$	Cospectrum $(T_1'T_2')$	Quadrature $(T_1'T_2')$	Phase Deg	Coherence
0.020	0.01242	0.00973	0.010051	0.003098	17	0.915
0.029	0.01575	0.01351	0.013851	0.002867	12	0.940
0.039	0.01151	0.01231	0.010089	0.004818	26	0.881
0.049	0.00493	0.00686	0.004282	0.001243	16	0.587
0.063	0.01345	0.01298	0.011269	0.003911	19	0.814
0.083	0.00399	0.00752	0.003009	0.001520	27	0.378
0.107	0.00333	0.00595	0.002522	0.000256	6	0.324
0.141	0.00460	0.00446	0.002153	0.001977	43	0.416
0.189	0.00294	0.00314	0.001013	0.000882	41	0.195
0.248	0.00249	0.00345	0.000088	0.000746	83	0.066
0.320	0.00239	0.00378	0.000708	0.000786	48	0.123
0.417	0.00213	0.00245	0.000347	0.000950	70	0.195
0.543	0.00178	0.00224	0.000216	0.000329	57	0.039
0.708	0.00117	0.00148	-0.000079	0.000093	130	0.009
0.920	0.00132	0.00114	0.000097	0.000087	42	0.011
1.197	0.00114	0.00099	0.000040	0.000046	49	0.003
1.550	0.00110	0.00081	0.000058	0.000063	48	0.008
2.010	0.00101	0.00065	-0.000029	0.000057	242	0.006
2.606	0.00088	0.00051	0.000018	0.000048	291	0.006
3.380	0.00087	0.00041	0.000018	0.000013	323	0.001
4.387	0.00099	0.00038	0.000017	0.000018	47	0.002

abrupt changes in the wind, pressure, and temperature fields associated with frontal passage are discontinuities that disrupt an otherwise regular oscillating pattern. Fourier analysis is not well suited for investigation of these intermittent processes, because it does not localize the event in time, and it requires multiple frequencies to represent discontinuities or intermittencies.

The limitations of Fourier analysis have led to the development of a technique known as wavelet analysis. Wavelets are zero-mean functions consisting of short oscillations localized in both time and frequency. A wavelet is characterized by a dilation factor which affects its size and amplitude and by a translation parameter which defines its origin or position within a time series. The wavelet transform is a convolution (the inverse transform of a cross-spectrum) of a wavelet with a time series. The resultant covariance product localizes small-scale features with fine spatial resolution, permitting a detailed analysis of intermittent phenomena that is not possible with traditional Fourier analysis.

Wavelet analysis is useful in locating intermittencies and discontinuities, because the product of the wavelet with time-series elements is greatest where the change in time-series element magnitude is greatest. The time series illustrated in figures 3.1 and 4.1 were subject to a discrete wavelet transform with the Lemarie-Meyer-Battle (LMB) wavelet basis using procedures developed by Kosteniuk (1993). Inverse wavelet transforms were then performed to separate the signal content by wavelet scale indices. Figures 4.2 and 4.3 present the unedited and edited v-component signal components at scale index 13 (corresponding roughly to a frequency of 2.5 Hz). Figure 4.2 contains large signatures for the data at 4-, 6-, and 8-meter levels corresponding to the noise spikes. The much-reduced signature amplitudes in figure 4.3 indicate that the large spikes have been removed by the despiking process.

The field of wavelet analysis has essentially developed since the 1980s with primary applications in optics, acoustics, and signal compression. A mathematical description of wavelets is presented by Meyer (1992). Among geophysical applications, wavelet analysis is being used to describe and model turbulence intermittencies (Farge, 1992; Collineau and Brunet, 1993). Because it offers the promise of localizing signal components by frequency and time, wavelet analysis should evolve into a powerful quality control tool.

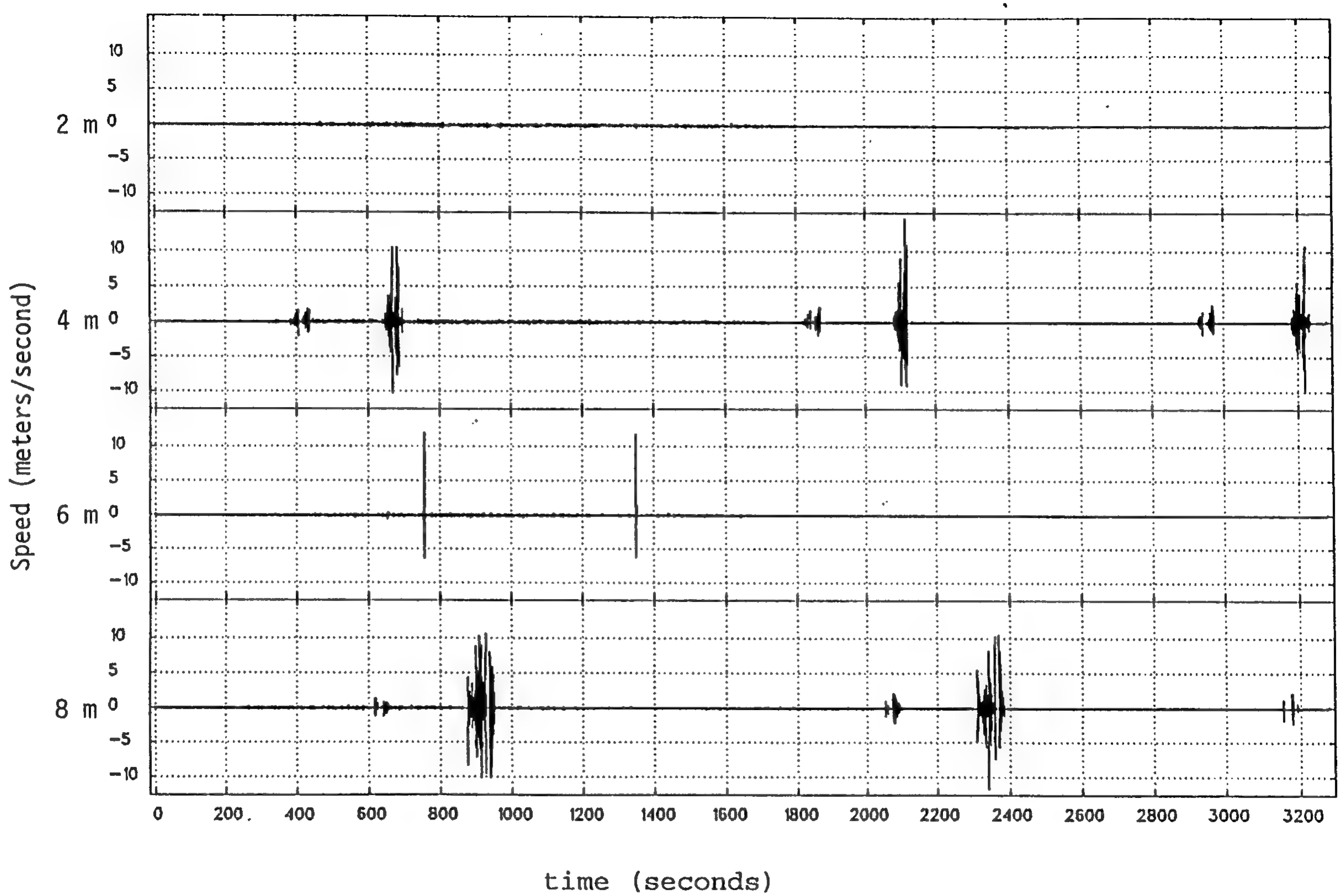

Figure 4-2. Unedited v-component sonic anemometer time series at wavelet scale index 13. (Note: The entire figure is autoscaled.)

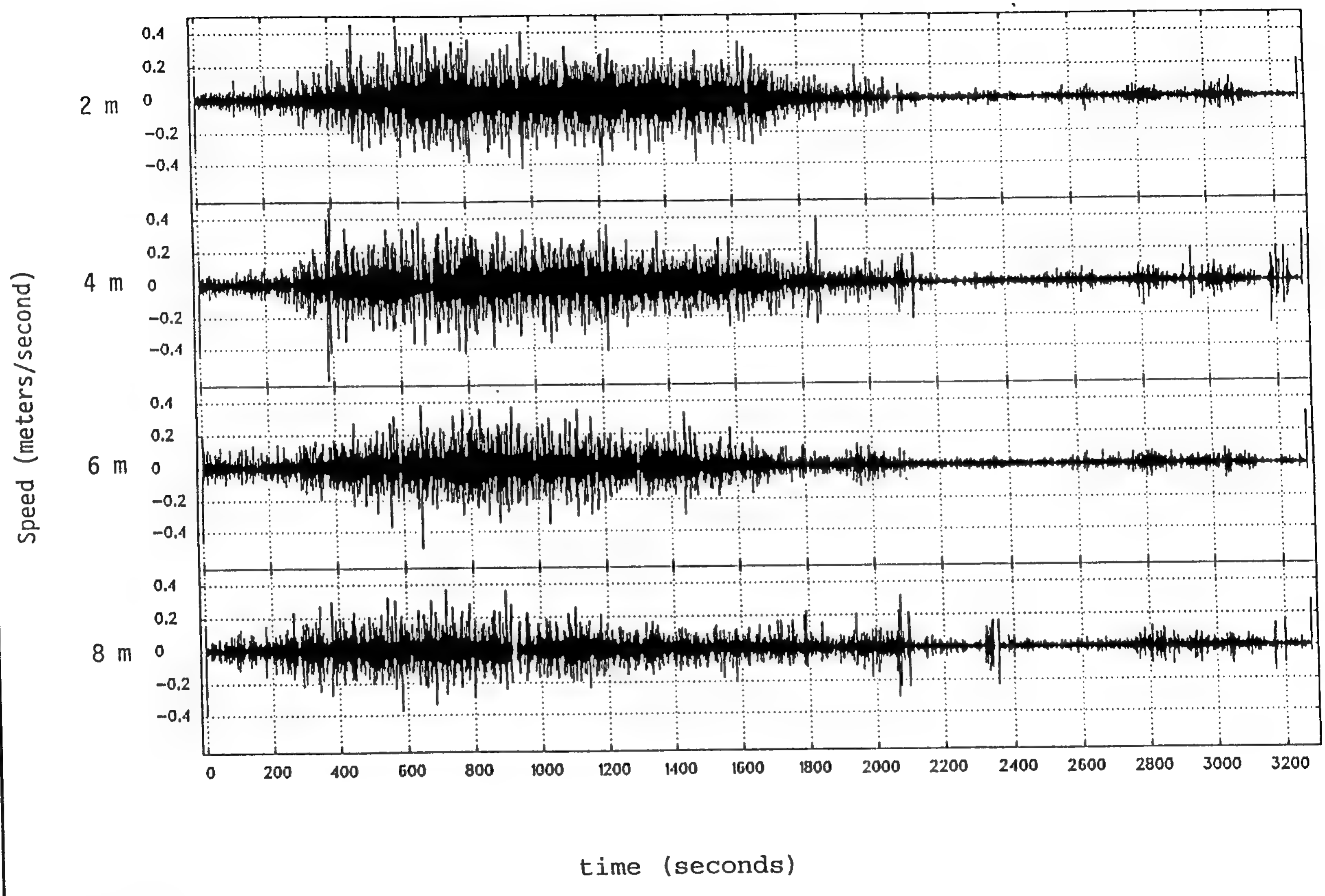

Figure 4-3. Edited v-component sonic anemometer time series at wavelet scale index 13.

4.6 Smoothers

In some situations, a smoothed average value or trend is more important than point-to-point detail which may contain noise or other undesirable characteristics. Smoothers remove unwanted high-frequency information to expose averages and trends that may otherwise be indiscernible in a fluctuating data field. Smoothers operate on the principle that noise is randomly distributed and can be removed from a data set by simple averaging. This assumption may not always be good, so a data set should be examined carefully before smoothing. Despiking may be needed prior to the smoothing operation.

Smoothing can be achieved by simple block averaging or by point-by-point replacement of each datum by the mean or median of its neighbors. Block averaging compresses the data set but may introduce discontinuities or jumps between successive nonoverlapping blocks. Replacement of each datum by a measure of central tendency produces a much smoother data set. Smoothing is used extensively for procedures like image restoration (Restrepo and Bovik, 1988) and for filtering out impulse noise (Palmieri and Boncelet, 1989). Smoothing of meteorological data is most useful for conservative variables such as pressure or potential temperature where consistency with known physical relationships is more important than the details of high-frequency variations.

APPENDIX A

INSTRUMENT FAULT CONDITIONS

A.1 Mechanical Anemometers

Mechanical anemometers are vulnerable to a variety of mechanical and electrical faults. These faults can usually be identified by spot checking the data.

A.1.1 Threshold Errors. Rotating mechanical wind instruments are mounted on low friction bearings. These bearings eventually wear down and accumulate dust causing bearing friction to increase. Because an increase in bearing friction requires an increase in turning torque to cause movement, the threshold speed is increased.

An increase in bearing friction is usually an imperceptibly slow process that is difficult to detect operationally. Performing threshold speed checks in a wind tunnel is the best way to define bearing wear. A simple (but nonquantitative) test of torque described in the draft Environmental Protection Agency (EPA QA) handbook (Lockhart, 1989A) is to roll the sensor housing slowly on a smooth, level, flat surface and observe the shaft. If the shaft turns with the sensor housing, the torque may not meet specification. A quantitative measure of torque on the turning shaft can be obtained using the R. M. Young torque disk. For field testing of mounted sensors, starting torque can be measured using precision torque instruments that fit onto the turning shaft. Available torque instruments of this type include the Waters torque watch and the Gm-cm torquemeter. Sensor manufacturers should be consulted about the torque sensor that works best with their instruments. A crude but effective bearing check for an installed propeller anemometer is to hang a small paper clip on one blade and observe the rotation of that blade towards the ground.

Threshold effects are difficult to observe unless wind speeds are bracketing the cup-breakaway speed. Near neighbor and velocity profile checks can aid in verifying anemometer performance, but bearing-drag problems can be most clearly observed by examining wind-speed histograms or distribution tables. Bearing drag should load the "calm" wind-speed bin at the expense of the next higher bin, as illustrated by the histograms in figure A.1.

A.1.2 Mechanical Anemometer Overspeeding. Mechanical anemometers require a certain amount of air to pass through them before they approach equilibrium with a new wind speed. This length of air passage remains fairly invariant over the sensor's linear operational range and is known as a distance constant (Lockhart, 1987). Because of their asymmetric drag, cup anemometers accelerate

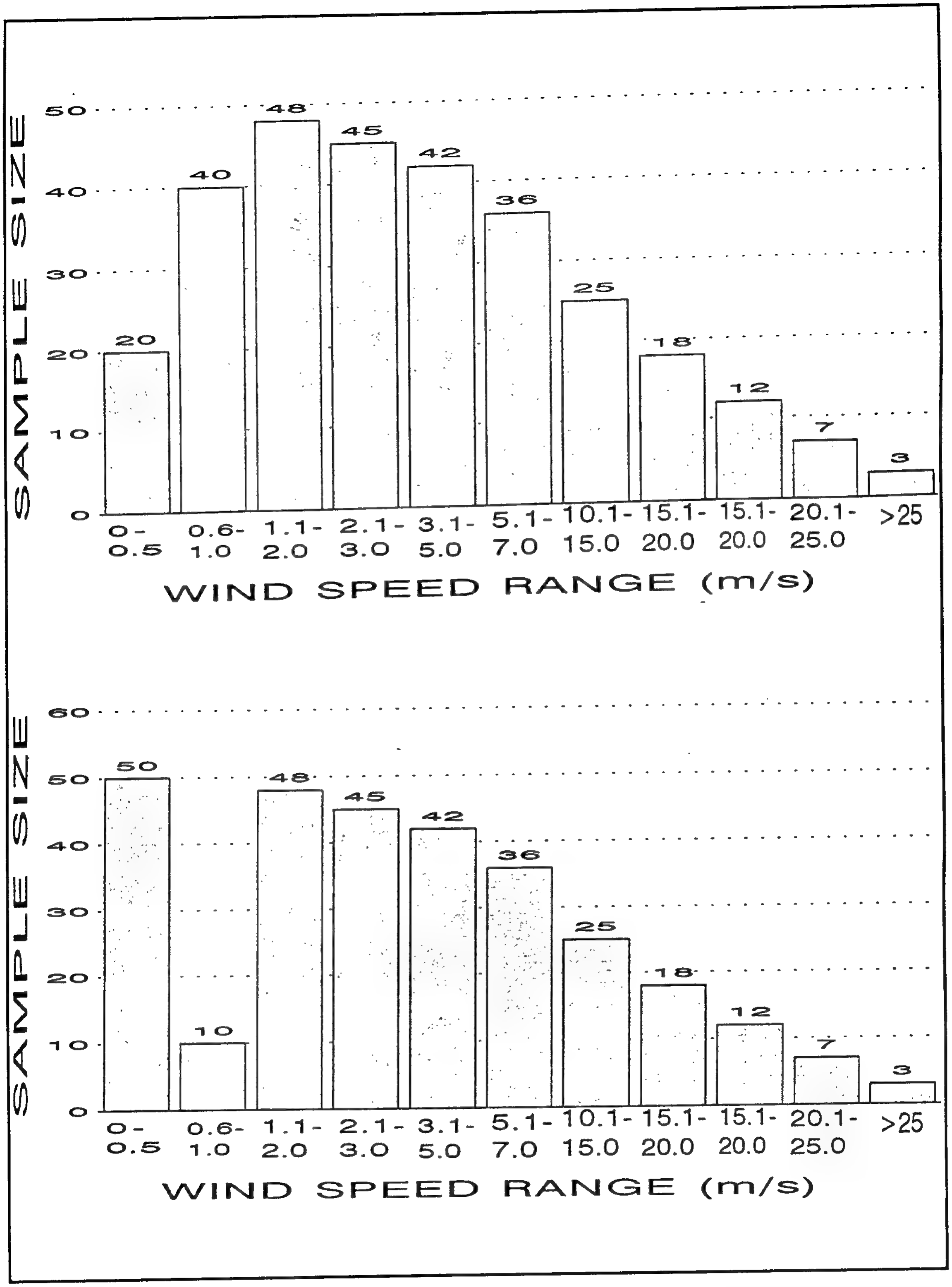

Figure A-1. Wind Speed Distribution Table for (a) a normally functioning anemometer speed distribution and (b) an anemometer exhibiting bearing drag.

faster than they decelerate, the result is a net overspeed condition in turbulent winds. The overspeed ranges from 1 to 10 percent depending on the scale and intensity of turbulence. Corrections are difficult to calculate, so this effect is usually overlooked; however, overspeeding can be minimized by proper placement of instrumentation. A site-selection criterion for cup anemometers should include minimum exposure to turbulent conditions such as locations in the wake of trees and buildings or in the proximity of rough surfaces. Helicoid-propeller anemometers are virtually symmetric and exhibit less overspeeding in turbulent conditions. Propeller anemometers may, therefore, be more suitable than cup anemometers for use in areas subjected to strong fluctuating wind conditions.

A.1.3 Sensor Damage. The aerodynamic performance of rotating anemometers is critically dependent on instrument balance and symmetry. If a blade or cup is misshapen, broken, or improperly installed, the sensor will still report data but performance will be degraded. This degradation results in uncharacteristic signal fluctuations, particularly at low wind speeds. Sensor damage can be detected by observing the variance or standard deviation of wind speed readings.

A.1.4 Battery Voltage. A 12-volt battery is often used to power mechanical anemometers and vanes. As the battery discharges and voltage drops, the operating span of the instruments decreases causing erroneous data. When battery voltage is used as a reference, this voltage should be monitored and reported on an additional data channel. When feasible, a battery charger should also be stationed at the measurement site.

A.1.5 Negative Wind Speed. A rotating anemometer may, under near-calm conditions, report a small negative wind speed (-0.1 m/s, for example). This negative wind speed may be an artifact of extension of the linear calibration curve into the sensor's nonlinear region. In this case, the instrument may not be in a true-fault condition unless there is supporting evidence to suggest otherwise.

A.1.6 Signal Check. An end-to-end signal check for a rotating anemometer can be accomplished in field conditions by removing the sensor head and installing a small motor driven shaft that rotates at a known rate. The output signal at the data-recording device is compared to the output expected for that rotation rate. This signal check verifies the performance of everything except the sensor head.

A.2 Wind Vanes

Electrical or mechanical faults that occur with wind vanes are usually associated with environmental degradation or animal-induced damage. The tail assembly is the component most susceptible to damage. Metal tail assemblies,

which offer greater damage resistance at the expense of responsiveness, may be needed at locations where tail damage is likely or at infrequently visited remote sites.

A.2.1 Potentiometer Errors. Dust or corrosion can cause dead spots or shorts on potentiometer-based wind equipment. A field check for this condition involves slowly rotating the vane both clockwise and counterclockwise through its entire electrical span while recording output. Note that wind vanes with two potentiometers have a 540° span. Changes in wind direction output should be smooth and continuous. A dead spot appears as a discontinuity in the reading. For plotted wind-vane data, a dead spot may appear as an unusual accumulation of data points within a very narrow range as the wind vane moves through the affected wind-direction section.

Wind-vane performance is not well characterized by means and standard deviations, particularly for data sets collected over extended periods of time. However, information can be gained by examining histograms or plots of the number of wind readings per wind-direction interval. A histogram with 36 bins (10° intervals) will usually be sufficient to identify faults with a vane's performance or exposure. The analyst should examine bins that contain unusually high or low numbers of wind readings. These wind-reading counts could indicate a problem with the equipment, with siting or exposure, or with the occurrence of interesting terrain-induced wind-flow patterns.

A.2.2 Bent or Damaged Vane. Wind vanes are susceptible to mechanical damage caused by environmental factors such as birds perching on the arms and of wind and radiation damage to the aerodynamic tail. A bent-vane arm can cause the tail to hang up on its supporting mount, which could appear in a histogram plot as an unusual absence of readings from certain wind directions coupled with an accumulation of readings from the point where the vane motion restriction occurs.

Damage to the aerodynamic tail of a vane may cause subtle changes in vane threshold, distance constant, and damping ratio that are unlikely to be detected in the field. Bent tails will impart a measurement bias and should be replaced. If a vane is used to generate wind variance information and noticeable portions of the tail are broken, the vane should be replaced. Wind vanes used to obtain mean-direction information only can perform reasonably well unless a major portion of the tail is missing.

A.2.3 Vane Imbalance. Wind vanes are balanced to align the balance point over the sensor's center shaft. Gross vane imbalance can cause the vane's threshold and damping ratio to deviate from manufacturer's specifications, resulting in unusually high or low wind direction variances.

A.3 Thermometers

Measurement representativeness, rather than instrument malfunction, is the major problem with thermometers. Thermometer sensors should be isolated as much as possible from electrical and environmental interferants.

A.3.1 Temperature Measurement Problem. Most temperature measurement sensors used for meteorological applications are of the immersion type, which includes probes that absorb energy from or emit energy to their surroundings. These thermometers are calibrated in stable thermal baths or chambers maintained by laboratories that can reference these baths to an acceptable temperature standard. Once calibrated, a thermometer will likely remain accurate until external influences such as foreign-substance deposits or corrosion compromise the sensor housing, or thermal and mechanical stresses alter the thermometer sensor. As long as a thermometer probe is not subject to unreasonable stress and the system is calibrated at suitable intervals, accuracy is usually not a problem.

The major problem with atmospheric-temperature measurements is representativeness. A condition in which the probe is in thermal equilibrium with the surrounding air is desired for meteorological temperature measurements. However, the air is fairly transparent to radiation and changes temperature primarily through convection, while the thermometer probe surface responds to solar radiation, convection, and conduction. Because the absorptance, conductance, and emittance of the probe and the air are different, the air and probe respond differently even when exposed to the same thermal and radiative environment. The result is that a thermometer probe mounted in the atmosphere is rarely in equilibrium with the surrounding air. Consequently, a thermometer can meet all criteria for accuracy and still provide measurements that are not representative of the true air temperature. Luers (1990) describes a methodology for estimating the temperature error on a common temperature probe, the rod thermistor.

A.3.2 Radiation Effects. Thermometer probes absorb and emit radiation at a much greater rate than the surrounding air. A typical unshielded probe will read temperatures higher than the surrounding air when exposed to direct sunlight during the day and lower temperatures at night. Probes are often installed in radiation shields to minimize this effect. Radiation shields with a ventilation rate of 3 to 5 m/s can reduce radiation errors to several tenths of a degree. Radiation shields should, if possible, be aspirated mechanically. Nonmechanical (naturally aspirated) shields are sometimes used at remote sites where power availability is limited. Measurement representativeness is degraded for sensors mounted in naturally aspirated shields during light wind conditions. Figure 10 in Wade (1987) illustrates the magnitude of the temperature error that can exist for a

typical temperature probe mounted in a naturally aspirated radiation shield. Lockhart (1989A) notes that it is critically important to maintain comparable aspiration rates over sensors used for temperature difference measurements. Jacobs and McNaughton (1994) find that a thin coat of optical white paint can significantly reduce solar-radiation absorption without causing adverse effects on sensor response.

A.3.3 Thermal Contact. Probe wires and supports provide heat sources or sinks for a temperature sensor. These thermometer components, like the probe itself, absorb and emit radiation. Heat transfer occurs anytime there is a temperature difference between the probe and the components to which it is connected. Careful probe design and an installation that thermally isolates the probe as much as possible can minimize these effects.

A.3.4 Foreign Substance Accumulation. The accumulation of foreign substances or the formation of oxide surfaces on the probe can change the probe's response time and radiative characteristics. Probes should be periodically inspected and cleaned or replaced to minimize these effects.

A.3.5 Field Checks. The sensor element performance can be checked in the field through use of one or more isothermal dewars. A dewar is characterized by a well-insulated core where temperature gradients are minimized. Temperature probes inserted into the dewar will quickly come into equilibrium with the interior of the dewar and produce a stable temperature reading. This procedure is particularly useful for checking the match of probes used for temperature differential (ΔT) measurements where interprobe functional precision is more important than absolute accuracy. For this purpose, Lockhart (1989A) recommends the use of several dewars, one chilled by ice, one kept to a temperature near 40 °C, and a third maintained near ambient conditions.

Exposure to electromagnetic radiation can be minimized by isolating the thermometer unit as much as possible from other equipment and by conditioning the electrical power. Long parallel cable runs should be avoided, particularly near power cables. Grounding should be stable and common between the sensor and data recorder.

A.3.6. Other Environmental Stresses. Other environmental stresses that impose noise or variable biases on ambient-air temperature measurements include thermal or mechanical shock, electromagnetic radiation, and self-heating. Resistance temperature detectors (RTDs) include a platinum alloy film or wire encased for protection in a glass or ceramic matrix. The coefficient of thermal expansion for the metal element and its matrix differ, and thermal shock causes stress on the element that may alter its calibration. All temperature probes, particularly quartz crystal, are susceptible to mechanical shock, which alters

calibration. The RTDs, thermocouples, and thermistors are subject to electromagnetic contamination, ground faults, or differences in ground between the probe and the data recorder. Noise from amplifiers and other system components and 60-Hz line noise may also degrade the measurement. Thermistors and, to a lesser extent, RTDs cannot completely dissipate heat generated by passage of current through the sensor elements. This excess heat produces a measurement bias. These effects are minimized through use of end-to-end signal checks, by intercomparing probes immersed in an isothermal dewar, and by minimizing exposure to environmental stresses.

End-to-end field-signal checks should detect system noise and bias not associated with the sensing element. These checks include replacing the sensor with a precision decade resistor and measuring the output at the data recorder. Biases can then be zeroed and noise can be traced. Several sequential signal checks may be needed to find low-frequency drift in the system.

A.4 Hygrometers

Hygrometer performance degradation is primarily due to contamination of the sensor or control surface. Frequent cleaning, recalibration, or sensor replacement may be needed to ensure data quality.

A.4.1 Lithium Chloride Dew Cell. The dew cell is a saturated salt dew point instrument with a sensor consisting of a fabric bobbin coated with lithium chloride (LiCl). An alternating current is passed through the salt coating to produce resistive heating. This heating causes evaporation from the hygroscopic LiCl solution with the rate of evaporation controlled by vapor pressure. As the bobbin loses water, resistance of the LiCl coating decreases. The bobbin cycles through heating and cooling until equilibrium with the atmospheric vapor pressure is reached. The equilibrium temperature is used as a measure of ambient dew point, with an accuracy near ±1 °C over a temperature span from -12 to +38 °C. The instrument operates within a range of 11 to 95 percent relative humidity, but performance declines markedly at humidities below 20 percent. Response is slow (dew cell response time is typically several minutes) because of bobbin thermal mass and the heating/cooling cycles; an averaging period of at least 15 minutes is recommended. The sensor should also be operated within an aspirated radiation shield. Exposure to water or excessive contamination will ruin the bobbin coating. Once set into operation, the instrument should be run continuously to prevent moisture accumulation from disturbing the LiCl coating. Recoating is a simple procedure easily accomplished in the field and should be done weekly to minimize contamination effects.

A.4.2 Chilled Mirror Hygrometer. Optical condensation hygrometers measure dew point by thermoelectric (Peltier) cooling of a polished mirror surface until

condensation occurs. Dew formation on the mirror interrupts a light beam to shut off the cooling process. A thermometer embedded in the mirror surface measures the dew point. These instruments are capable of operation over greater temperature and humidity ranges than most other hygrometers designed for field use.

The response of an optical condensation hygrometer is limited by the finite time required to condense or evaporate a film on the controlling mirror surface. Accuracies of ±0.5 °C or better are possible. Operator adjustments for "gain," "compensation," and "thickness" affect instrument performance. Gain controls the system-dynamic response, while compensation is a phase lead to the amplifier circuit to compensate for the phase lag of the Peltier cooler. This compensation dampens oscillations to allow a higher gain setting and to improve dynamic performance. Thickness controls the depth of the film allowed on the mirror before cooling is interrupted. The thickness adjustment offers a compromise between fast dynamic response and insensitivity to mirror contamination. Skill and patience are needed to optimize these adjustments, although microcontroller technology has recently been used to automate the adjustment procedure.

The cooling rate of the Peltier cooler in an optical condensation hygrometer is rapid, but settling time is inversely proportional to vapor pressure. For very low vapor pressures (usually associated with temperatures below -18 °C), the small amount of water vapor present may require several tens of minutes to form the required condensate thickness on the controlling mirror. In spite of the increased time constant, the optical condensation hygrometer produces useful data at cold temperatures where the response of most other humidity sensors is poor. An additional complication at temperatures between 0 and -30 °C is that either dew or frost may form on the mirror surface. The possibility of accumulating either dew or frost creates a measurement ambiguity unless freezing is artificially initiated on the mirror.

The mirror surface of the optical condensation hygrometer is relatively insensitive to contamination, although cleaning every 2 or 3 days is recommended in a very dusty environment. Mirror self-cleaning procedures are generally ineffective in high dust concentrations. Dirty mirror surfaces can cause the equipment to oscillate about the condensation point.

A.4.3 Adsorption Hygrometers. An adsorption hygrometer's sensor electrically measures the percent relative humidity based on changes in conductivity, capacitance, or resistance because of adsorption or desorption of moisture as humidity changes. These hygrometers typically operate over a humidity range of 10 to 98 percent. Soluble salts, halogens, or any substance that alters surface resistivity can decalibrate or destroy this type of sensor. Consequently, these instruments should not be used in highly contaminated environments. If temperature-compensated and mounted in an aspirated radiation shield,

adsorption hygrometers can produce accuracies of ±2 to 5 percent over a limited range of temperatures. Major accuracy problems are likely at cold (-20 °C) temperatures, and significant calibration drift and sensor failures can occur in a marine environment. Some instruments exhibit noticeable hysteresis effects, particularly following long exposure at saturation.

Modern relative humidity (RH) sensors are generally thin-film capacitors designed to change capacitance as a function of moisture adsorbed onto the surface. The primary source of error is surface contamination which appears as a bias in the reading. Shielding is used to protect the sensor, but airborne contaminants eventually accumulate on exposed surfaces. Errors can appear as a slow drift of calibration or as an abrupt shift in the humidity value. Field checks against an uncontaminated instrument can be used to verify performance. Immersion of the sensor into a capsule with controlled humidity is a more time consuming but effective check. Some humidity sensor manufacturers provide capsules for this purpose with humidity controlled by saturated salt solutions, typically ranging from 20 to 80 percent RH.

A.4.4 Lyman-α Hygrometers. The Lyman-α hygrometer offers a fast-response fine-scale water-vapor fluctuation measurement capability. Instrument operation is based on Beer's law absorption of light at the Lyman-α (121.5-nm) wavelength by the hydrogen constituent of water molecules. The sensor consists of a glow discharge tube and a detector tube connected to an electrometer circuit with the detector set behind a magnesium fluoride window. A gap of 0.5 to 2 cm between the source and detector offers fine spatial resolution at the expense of significant flow distortion effects. The window is sensitive to etching and contamination, making the Lyman-α subject to rapid calibration drift. Consequently, the Lyman-α hygrometer is often used in conjunction with a slow-response reference instrument such as a chilled mirror hygrometer. Buck (1985) describes principles of a Lyman-α hygrometer, and Lind and Shaw (1991) describe techniques for adjusting Lyman-α calibration for airborne measurements.

A.4.5 Infrared Hygrometers. Infrared hygrometers use closely spaced columnated beams of infrared light and a differential absorption technique to measure absolute humidity. These instruments have a transmitter which sends out two parallel beams closely spaced in frequency, but with different water vapor absorption characteristics. The ratio of the energy received from the absorbing and nonabsorbing beams is proportional to the absolute humidity in the sampled volume. With sealed-optics and nonreactive-sensor plates, optical-humidity sensors are relatively insensitive to contamination, are capable of operation at extreme temperatures without degradation, and provide high data rates. Internal calibration checks minimize calibration drift. Variations in chopper-motor speed and instrument casing temperature can cause erroneous readings.

A.4.6 Psychrometer. The psychrometer consists of two matched thermometers mounted together in a holder. One thermometer bulb is exposed to ambient-air conditions (the dry bulb) and the other is covered by a wet-muslin sock (the wet bulb). When the thermometers are aspirated, evaporative cooling of the wet bulb lowers its temperature. The difference between dry and wet bulb temperatures is the wet-bulb depression. Standard meteorological tables relate dry bulb temperature and wet bulb depression to relative humidity and dew point. Some psychrometers have been automated but most are used manually. Psychrometers can provide very accurate readings for temperatures above 0 °C and high humidities. At low humidities, a significant amount of energy must be dissipated by evaporative cooling for the wet bulb to reach equilibrium. At this point, the aspiration rate becomes a crucial limitation on accuracy. At temperatures below 0 °C, the wet bulb can be either liquid or frozen, each with unique thermodynamic equilibrium values. Accuracy is a function of the care with which the wet-bulb reading is taken. Factors limiting accuracy include cleanliness of the muslin sock, water purity, and effects of water temperature on wet-bulb readings. Measurement precision of a liquid-in-glass psychrometer is limited by the ability of the observer to resolve the thermometer's temperature scales; scale readings finer than 0.1 °C are probably not meaningful. The dynamic response of a psychrometer is usually slow, although Tsukamoto (1986) describes a fast fine-wire psychrometer used for water vapor flux measurements.

A.5 Actinometers

Actinometers should be mounted level (or at a specific chosen angle) on a rigid surface free of obstructions above the plane of the sensing element.

A.5.1 Foreign Substance Accumulation on Dome. Exposed sensor surfaces or domes are susceptible to foreign substance accumulation. These surfaces require periodic inspection and cleaning.

A.5.2 Calibration Drift. Exposure of the instruments to wide temperature changes or thermal gradients may cause the instrument to drift off calibration.

A.5.3 Humidity. Moisture trapped inside the dome covering the sensor causes erroneous readings and is minimized through the use of a desiccant. The desiccant should be inspected and changed as necessary to minimize moisture accumulation.

A.5.4 Exposure Blockage. Care should be taken to avoid inadvertent shadowing of solar radiation sensors. The instrument site should be selected to ensure that trees, buildings, or other structure do not cast a shadow on the instrument during any part of the day when data are required. Reflections from nearby objects such

as windows or bright sheet metal should be avoided. It is desirable to choose a site where all obstacles subtend an angle of less than 10° above the horizon.

A.6 Barometer/Altimeter

Some modern pressure sensors are hand-held devices that serve as altimeters as well as pressure sensors. These instruments are designed for field use and are usually temperature compensated to provide accurate altimetry. Older style barometers of the mercury-in-glass and aneroid type do not travel well and should be kept in stable environments where they are not subject to abrupt temperature or pressure changes.

Exposure is a major consideration for barometers, especially those located inside buildings. Indoor pressure changes occur as doors open or close and as air conditioning units cycle on or off. Exposure to outside pressure can be established through an orifice, but the opening can become blocked by debris or damage to the connecting tube. Building wake effects may influence pressure readings during high winds. Mechanical shock can decalibrate an instrument.

A.7 Aerosol Samplers

Unlike atmospheric gases, it cannot be assumed that aerosols suspended in the air will be well mixed. Aerosol behavior is governed by inertial effects, settling velocities, electrostatic effects, and shape factors. The aerosol content of the air is measured by inertial impaction, dosimetry, and by nephelometry. Each of these measurement techniques is affected by the characteristics of the aerosol to be measured. Although calibration of aerosol samplers is relatively straightforward and subject to few fault conditions, obtaining a sample that is truly representative of the ambient-aerosol distribution can be difficult. Aerosols are found on scales ranging from less than one micron to over 100 microns in diameter with behaviors that are dependent on their size, shape, and chemical makeup. Unrepresentative aerosol sampling typically occurs for the following reasons:

1. samplers located where they are inadequately exposed to the aerosol or are blocked by other objects;

2. mismatch between wind speed and sampler flow velocity or misalignment of sampler in the flow (nonisokinetic effects);

3. lack of pre- and post-test baselines;

4. sampling time so short that an insufficient sample is obtained for analysis, or so long that filters, optics, or inlets become overloaded or blocked;

5. particle shape or electrostatic effects skew the sample; and

6. aerosol cloud is too thin or too dense for the chosen sampler.

A.7.1 Inertial Impactors. Inertial impactors are used to obtain mass measurements of aerosol content, usually with the total mass separated into size ranges. The performance of inertial impactors is dependent on inertial particle-size separation as the aerosol cloud passes over various flow obstructions. A particle's behavior is assumed to vary with its equivalent diameter, adhering to collector plates by electrostatic and Van der Waals forces. Larger and denser particles typically are the first to contact the impactor, although impaction and separation is a stochastic process with an overlap in size ranges. Collection efficiency varies with particle size, shape, density, and electrostatic charge. Particles that have facets or points tend to accumulate charge, while round particles are less likely to retain electric charges. Atmospheric moisture content also affects collection efficiency. Inertial impactors should be operated for a sufficient length of time to accumulate a large enough mass for measurement. Measurement accuracy is dependent on how accurately the accumulated particle masses can be weighed.

A.7.2 Dosimeters. Dosimeters include filters that collect particles by diffusion, inertial separation, and direct interception; electrical charges on the particles and filters generally increases collection efficiency. If sampling is continued too long, filter collection efficiency decreases as aerosols bypass the clogged filter. Dosage is calculated as a function of the mass of material collected, divided by volumetric flow rate. (NOTE: The effects of measurement site pressures must be considered if volumetric flow rates taken at different sites are to be compared.) Dosimeters obtain their most representative samples when the flow rate is matched with the speed at which the wind propels aerosols towards the filter. Representativeness is therefore a function of inlet geometry, orientation with respect to the wind, and the degree to which the flow rate is matched to wind speed (isokinetic sampling). It is difficult to obtain representative dosimeter measurements for particle sizes larger than 25 microns.

A.7.3 Nephelometers. Nephelometers operate by nonextractive optical techniques, defining aerosol density using light scattering or laser-Doppler velocimetry. Nephelometer calibration is performed using standard polystyrene latex beads available from National Institute of Standards and Technology (NIST) or commercial sources. Light-scattering systems have measurement uncertainties because of nonspherical particle shapes and aerosol refractive-index variations. Assuming constant particle shape and density, laser velocimetry uses particle-velocity measurements in an accelerating flow field to define size. Nephelometry produces unrepresentative readings if the aerosol is so dense that multiple scattering of the light occurs, if particle collisions alter the size distribution during the sampling period, or if the aerosol accumulates on the system optics.

A.8 Scintillometers

A scintillometer is a ground-based remote-sensing instrument designed to measure crosswind components and optical turbulence intensity along a line-of-sight path established between a transmitter and a downrange receiver (see Range Commanders Council document 381-92, Meteorological Measurements Guide). Typical scintillometer operating range is 0 to 20 m/s for crosswinds and 10^{-16} to 10^{-12} for the refractive index structure parameter (C_n^2). The pathlength between transmitter and receiver can range from a few hundred meters to several kilometers, depending on the along-path turbulence intensity. Excessive turbulence causes signal saturation, where the relationship between the log amplitude of the variance of signal intensity and C_n^2 is no longer linear. Newer scintillometer models can compensate for some intrusion into the nonlinear region, but saturation should be avoided to preserve data quality. The theory and performance of a recent model crosswind profiling scintillometer is described by Ochs et al. (1992).

Because scintillometers sense changes in the intensity and position of optical turbulence as the basis for measurement, they are sensitive to platform vibrations and must be mounted on solid, vibration-free platforms. Transmitter and receiver optics must also be protected from direct intrusion of sunlight. Optical-path positions must be carefully chosen or shaded to avoid direct sun, or damage may occur. Scintillometer transmitters and receivers can be set up to operate inside buildings through windows as long as excessive glare or reflected light does not enter the optics. Scintillometer signals are modulated to minimize interference from background movement, but excessive movement in the receiver's field of view can induce noise. For example, the optical path should not be established where road traffic is moving behind the transmitter. Objects moving across the optical path between the transmitter and receiver causes signal loss.

A.9 Sonic Anemometer/Thermometers

A sonic anemometer/thermometer consists of a transducer array containing paired sets of acoustic transmitters and receivers, a system clock, and microprocessor circuitry for measuring intervals of time between transmission and reception of sound pulses. Wind velocity and the speed of sound can be calculated from measurements of the transit time of an acoustic wavefront along the known path between pairs of transmitter/receivers. Measurements are made along one, two, or three axes to define components of the three-dimensional windfield. Measurement accuracy is a function of how precisely time is measured and how precisely the acoustic pathlength is known. Factors adversely affecting measurement accuracy include changes in acoustic pathlength caused by mechanical or thermal stress, distortion or attenuation of the acoustic wavefront, or changes in the transducers or electronic circuitry (decalibration). Flow distortion and

blockage by the transducers or the supporting array can adversely affect the velocity component measurement representativeness.

Sonic anemometer/thermometer fault conditions occur when the acoustic wavefront is distorted or blocked, when the transducers or electronics fail or become unstable, or when calibration is lost. The ultrasonic pulse emitted by the transmitter is sensitive to environmental interference (nearby explosions or jet aircraft), to acoustic reflections from objects placed too close to the acoustic array, or to attenuation or blockage by precipitation, dust particles, or insects on the transducers. Nonreceipt of an acoustic wavefront usually causes a no-data condition. Noise or intermittent transducer failures appear as noise spikes. Thermal and mechanical shock may cause decalibration. (Calibration can be verified in the field through use of a zero-wind chamber.)

A.10 Constant Temperature Anemometers

Constant temperature anemometer (CTA) systems consist of amplifiers, a data-acquisition system, and a hot-wire or hot-film element mounted in a Wheatstone bridge that is balanced to maintain the sensor at a control temperature well above the ambient temperature. As wind blowing across the sensor cools the heated element, the bridge network responds by sending current through the element until balance is restored. System electronics sense and record the resulting voltage changes across the bridge. The heat loss experienced by the element (parameterized by the Nusselt number Nu) is related to the flow velocity (parameterized by Reynolds number Re) across the element by

$$Nu = A + B\,Re^{p} \tag{A-1}$$

where A and B are empirical constants and p is a velocity-dependent exponent varying from 0.45 to 0.51.

Misorientation and contamination are the major sources of error with a CTA. The constant-temperature element is most sensitive to the flow component normal to it. Except for omnidirectional sensors, the element should be carefully aligned into the flow to be measured. Caps and baffles are often used to protect the sensor from moisture and contamination. This housing distorts the flow, and eddies shed from probe support structures can cause unrepresentative readings. Accumulation of rime ice, snow, or dust on the sensor causes decalibration, and accumulations on the sensor housing increase flow blockage. When operated in high-speed flows, a sensor may vibrate. Vibration causes a strain on the elements which leads to changes in wire resistance. The use of low-resistance wires or films and low-voltage signals also makes these instruments sensitive to electromagnetic-field changes, electronic noise, power-supply noise, and zeroing drift.

Because convective cooling on the surface of a CTA sensor is a molecular heat-exchange process, the relationship between cooling and wind speed should be density compensated (compensated for changes in both temperature and pressure). Therefore, a CTA system calibrated at standard temperature and pressure (STP) would not be in calibration for operation at conditions that differ from STP. Because of the nonlinear relationship between velocity and cooling, calibrations should include several points spanning the intended operating range of the instrument. Practices for using CTA systems for ground-based and aircraft measurements are described by Lenschow (1986).

A.11 Field Mill

Field mills are electromechanical devices designed to measure the electric field over flat surfaces where the fair weather potential gradient is uniform. The mill consists of a rotating, grounded, fanlike plate that chops the electric field lines by alternately covering and uncovering plates called stators. The stators charge and discharge in proportion to the amplitude of the electric field, and the resulting modulated charge is converted to voltage for output to a recording device.

Variations in site characteristics, contamination, and mechanical failure are the three major sources of error for field mills. If a field mill is located near tall objects, the electric-field amplitude will be altered. A mill surrounded by a 25-foot radius of gravel, a 50-foot radius of cleared vegetation, and with no obstructions subtending an angle of greater than 18° above the horizon is likely to have a sufficiently uniform fair weather potential gradient. Other site-dependent characteristics include the proximity of sources of charged particles such as vehicular exhaust, nearby power lines, or blowing sand or dust. Roughening of plate surfaces that occurs with corrosion or contamination causes premature plate discharge, plate insulation, or physical contact between the rotor and stator. Field mills are not very sensitive to changes in rotor speed and will not function if rotation ceases.

Field mills used in a network are usually mounted and calibrated with the same geometric and electrical characteristics. Mounting the mill in an inverted configuration minimizes the effect of rain or particulate deposition on the plates. When operated in a network, a comparison of the outputs of adjacent mills can be used as a field check of mill performance. Systematic differences between nearby mills that persist for an hour or more are suspect and should be investigated. After heavy storm activity, mill calibration should be performed to verify that the sensor and support electronics were not damaged by lightning.

APPENDIX B

INSTRUMENT QUALITY CONTROL CHECKS

FLAGGING CRITERIA

This appendix contains flagging criteria with nominal numerical values that pertain to a mid-latitude site with open exposure in flat terrain and nonextreme weather conditions. Some criteria will work better at certain sites than at others. Numerical values should be adjusted for site-specific conditions.

B.1 Rotating Anemometer QC Checks

FLAGGING CRITERIA FOR ROTATING ANEMOMETERS

(1) Scalar wind speed <0.1 or greater than 19.9 m/s (or similar user-defined maximum-minimum criteria derived from equipment operating range)*

(2) Wind speed >2 m/s and increases or decreases by a factor of 2 or greater between wind readings (inadequate sensor exposure).

(3) Wind speed makes a step increase from calm to >1 m/s. (Worn bearings or ice-bound sensor is likely.)

(4) Wind speed remains calm or at a constant value for successive averaging periods up to 1 hour (sensor stuck in position).

(5) Point on wind-speed profile deviates from profile mean by >0.5 m/s (possible bearing drag).

(6) Battery voltage drops below system reference voltage.

(7) Difference between maximum and minimum wind speeds exceeds the average wind speed by a factor of 2. (Average possibly contaminated by noise spikes or signal drop-out.)

*Because of the nonlinear response of rotating anemometers at low speeds, the calibration curve for some instruments may cause a small negative wind reading (-0.1, for example) during calm winds. Flagging criteria may require adjustment to accommodate this condition.

B.2 Wind Vane QC Checks

FLAGGING CRITERIA FOR WIND VANES

(1) Wind direction remains constant for 1 hour. (Vane is stuck in position.)

(2) Wind speed is >2 m/s and wind-direction standard deviation is less than 1° or greater than 60°. (Vane is stuck in position or inadequately exposed.)

(3) Wind speed is >2 m/s and wind direction changes by more than 45° between successive readings (inadequate vane exposure).

(4) Wind speed is >2 m/s and point on wind-direction profile deviates from profile mean by more than 45°.

(5) The modal (most frequent) wind direction reading does not change between successive averages (dead spot on potentiometer).

(6) Battery voltage drops below system reference value.

B.3 Thermometer QC Checks

FLAGGING CRITERIA FOR THERMOMETERS

(1) Temperature remains invariant or changes less than 0.1 °C within a 15-60 minute averaging period.

(2) Temperature readings exceed climatological extremes (minima or maxima) for the measurement site (inadequate sensor exposure).

(3) Temperature change in excess of 10 °C per hour (inadequate sensor exposure).

(4) Data point deviates from temperature profile by >0.5 °C (for mechanically aspirated ΔT system) (aspiration motor failure or calibration drift).

(5) Temperature standard deviation exceeds 2 °C for an averaging period of 1 hour or less (possible spikes or inadequate sensor exposure).

(6) Difference between temperature maximum and minimum for a 15-60 minimum averaging period is zero or greater than 10 °C (sensor failure or spikes).

(7) Persistent autoconvective lapse rate is present in temperature profile.

B.4 Dew Point Instrument QC Checks

FLAGGING CRITERIA FOR DEW POINT INSTRUMENTS

(1) Dew point equals or exceeds companion temperature measurement (inadequate sensor exposure/no evaporative cooling).

(2) Dew point exceeds expected climatological maximum or minimum (inadequate sensor exposure).

(3) Dew point change exceeds 10 °C within 1 hour (aspiration failure or sensor contamination).

(4) Dew point standard deviation exceeds 1 °C (spikes in data).

(5) Difference between dew point maximum and minimum is zero or greater than 10 °C over the averaging period (spikes in data).

(6) Dew point oscillation (control surface contaminated).

B.5 Humidity Instrument QC Checks

FLAGGING CRITERIA FOR RELATIVE HUMIDITY INSTRUMENTS

(1) Humidity reads ≤ 0 or ≥ 100 percent (inoperative sensor or no signal).

(2) Humidity reading remains constant over a period of 2 or more hours (condensation or sensor or hysteresis effects).

(3) Humidity changes by 30 percent in 1 hour or less (sensor contamination).

B.6 Pressure Sensor QC Checks

FLAGGING CRITERIA FOR PRESSURE INSTRUMENTS

(1) Pressure difference from climatological mean station pressure by ±25 mb (calibration error).

(2) Pressure change exceeds 3 mb in one hour (inadequate exposure).

(3) Pressure change of 0.1 mb or less over a 24-hour period (sensor failure or inadequate exposure).

(4) Difference between maximum and minimum pressure over a 24-hour period exceeds 15 mb (inadequate exposure).

B.7 Actinometer QC Checks

FLAGGING CRITERIA FOR ACTINOMETERS

(1) Incoming solar radiation exceeds solar constant ($\sim$1400 W m^{-2}) (calibration drift or inadequate exposure).

(2) Zero incoming radiation during daylight hours (sensor failure).

(3) Incoming radiation exceeds 100 W m^{-2} at night (calibration drift).

(4) No change in radiation reading over a period of 2 or more hours during daylight hours (loss of sensitivity).

(5) A drop in radiation readings not associated with sunrise or sunset occurs at approximately the same time of day for 3 or more successive days (possible partial sensor shadowing).

B.8 Visibility Sensor QC Checks

FLAGGING CRITERIA FOR VISIBILITY SENSORS

(1) Unexplained zero or full scale readings for several successive hours (instrument failure).

(2) Visibility reading includes intermittent sharp spikes (intermittent optical path interruption or loss of signal).

B.9 Sonic Anemometer/Thermometer QC Checks

FLAGGING CRITERIA FOR SONIC ANEMOMETER/THERMOMETERS

(1) Data within averaging interval include ± full scale readings (intermittent transducer faults).

(2) Readings are invariant during averaging period (electronics fault).

(3) Intermittent data spikes (interference from transient acoustic or electronic sources, or precipitation striking the transducers).

B.10 Aerosol Sampler QC Checks

FLAGGING CRITERIA FOR AEROSOL SAMPLERS
(1) Particle distribution is monodisperse (calibration inadequate).
(2) Background readings are unstable and include sharp spikes (electronics fault).

B.11 Constant Temperature Anemometers

FLAGGING CRITERIA FOR CONSTANT TEMPERATURE ANEMOMETERS

(1) Sudden "ping" or change in signal level (probe contamination).

(2) Increase in noise level (electromagnetic contamination or electronics fault).

(3) Suspect changes in signal characteristics (straining of element caused by vibration, change in probe orientation with respect to wind, or probe housing blockage).

B.12 Field Mills

FLAGGING CRITERIA FOR FIELD MILLS

(1) Constant large readings during fair-weather conditions (contamination of the mill or a support electronics fault).

(2) Sensor data that appear stormlike during fair weather conditions. (Blowing dust and sand contain charged particles that can produce a stormlike response.)

NOTE: The mill motor must be operating to produce data. If a motor fault bit is available from the mill support electronics, then the operating software should use the state of this bit to determine the validity of the data. If no fault bit is available, the sensor should be checked daily for motor operation.

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